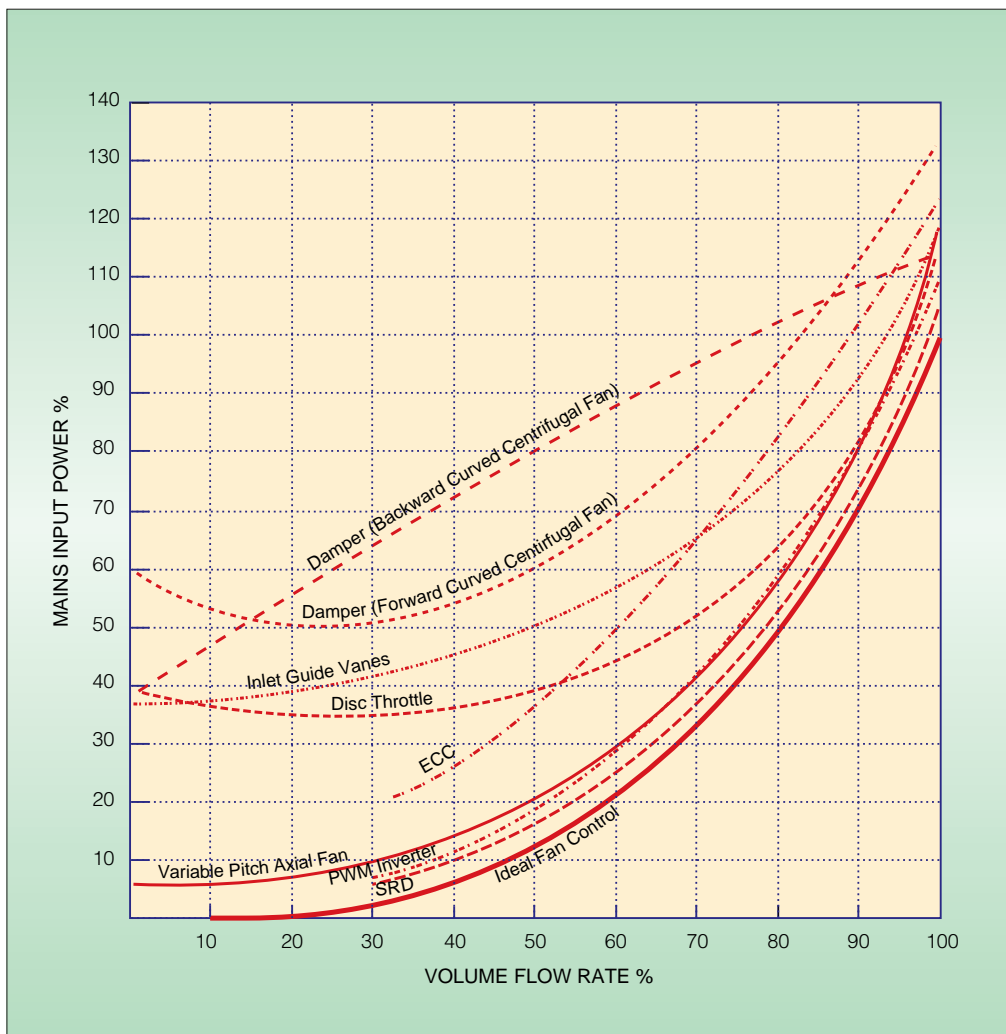


## Variable flow control



March 1996

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## **Variable flow control**

Prepared for the Department of the Environment by

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## CONTENTS

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	Page
<b>1. Introduction</b>	<b>1</b>
1.1 Overall Objectives	1
1.2 Scope	1
1.3 Guidance	2
1.4 Further information	2
1.5 Acknowledgements	2
<b>2. Fan and Pump Laws</b>	<b>3</b>
2.1 Fan Laws	3
2.2 Pump Laws	3
<b>3. Variable Flow Control Methods</b>	<b>4</b>
3.1 Fans	4
3.2 Pumps	5
3.3 Belt and Direct Drives	5
3.3.1 Belt Drives	5
3.3.2 Direct Drives	6
3.4 Shared Duty and Standby	7
<b>4. Comparative Efficiencies of Variable Flow Control Methods</b>	<b>8</b>
<b>5. System Regulation</b>	<b>9</b>
5.1 Traditional Methods	9
5.2 Regulation via VSDs	9
5.3 Regulation Conclusions	14
5.4 Existing Installations	14
5.5 Water Flow Measurement	15
5.6 Axial Fans	15
<b>6. Variable Flow Control Energy Savings</b>	<b>16</b>
6.1 Office Building, Heating Pumps	16
6.2 Airport Building, Chilled Water Pumps	17
<b>7. Variable Speed Drives</b>	<b>18</b>
7.1 Eddy Current Couplings	18
7.2. Frequency Inverters	18
7.2.1 Current Source Inverters	19
7.2.2 Pulse Amplitude Modulation Inverters	19
7.2.3 Pulse Width Modulation Inverters	20
7.2.4 Voltage Vector Control Inverter	20
7.2.5 Flux Vector Control Inverter	20
7.3 Switched Reluctance Drives	21
7.4. Multi Speed Motors	22
7.5. Variable Voltage	22
7.5.1 Electronic Variable Voltage VSDs	22
7.5.2 Variable Auto Transformer VSDs	22
7.6 DC VSDs	23

---

<b>8. Mechanical Variable Flow Controls</b>	<b>24</b>
8.1 Variable Pitch Axial Fans	24
8.2 Inlet Guide Vanes	24
8.3 Disc Throttles	25
8.4 Dampers	25
8.5 Regulating Valves	25

---

<b>9. Variable Flow Control Applications</b>	<b>26</b>
9.1 Variable Air Volume Air-Conditioning Systems	26
9.1.1 VAV Control Types	27
9.1.2 VAV Box Temperature Control	27
9.1.3 VAV Box Volume Control	28
9.1.4 Series Fan Assisted VAV Boxes	28
9.1.5 Parallel Fan Assisted VAV Boxes	28
9.1.6 Static Pressure Supply Fan Control	28
9.1.7 Static Pressure Reset Supply Fan Control	28
9.1.8 Demand Based Supply Fan Control	29
9.1.9 Fan Type	29
9.1.10 Extract Fan Volume Control	29
9.1.11 Velocity Sensing	29
9.1.12 Calibrated Volumetric Output From Fans	30
9.1.13 Fixed Schedule Extract Fan Control	30
9.1.14 Space Differential Pressure Sensing	30
9.1.15 Filter Status	30
9.2 Air Quality Control	31
9.2.1 Recirculation Systems	31
9.2.2 Full Fresh Air Systems	31
9.2.3 CO <sub>2</sub> (carbon dioxide) Air Quality Sensors	33
9.2.4 Multiple Contaminant Air Quality Sensors	33
9.3 Heating/Cooling Demand Control	33
9.4 Cooling Tower Fan Control	34
9.5 Dry Air Cooler Fan Control	34
9.6 Variable Flow Heating and Chilled Water Systems	35
9.6.1 Control Valves	35
9.6.2 TRVs	36
9.6.3 Differential Pressure Control	37
9.6.4 Maximum Differential Pressure Control of System Legs	37
9.6.5 Automatic Flow Control Valves	39
9.6.6 Zoning of Circuits	39
9.7 Circuit Interaction	39
9.8 Pump Configuration	39
9.9 Single Pipe Systems	40
9.10 Maximum Demand Control	40
9.11 Smoke Extract	40

---

<b>10. Variable Flow Control Selection Procedures</b>	<b>41</b>
10.1 Fan Type	41
10.2 Pump Type	41
10.3 Fan and Pump Selection	41
10.4 Shared Duty	41
10.5 Capital Cost	43

10.6	Fan Space	44
10.7	VSD Space	44
10.8	Drive Type	44
10.9	EMC and Harmonics	45
10.10	Resonance and Pulsation	45
10.11	Noise	45
10.12	Installation	45
10.13	Maintenance	45
10.14	Selection Based on Cost Benefit Analysis	46
	10.14.1 Costs and Benefits	46
	10.14.2 Sensitivity	46
	10.14.3 Analysis Methods	46
	10.14.4 Simple Payback	46
	10.14.5 Accounting Rate of Return	47
	10.14.6 Discounted Cash Flow (DCF)	47

---

<b>11.</b>	<b>Engineering and Installations</b>	<b>49</b>
11.1	Introduction	49
11.2	Integration into Systems	49
11.3	Electromagnetic Compatibility	49
11.4	Harmonics	50
	11.4.1 Standards	51
	11.4.2 Filters	52
	11.4.3 Power Factor Correction	53
11.5	Reliability	53
	11.5.1 Mechanical Flow Control Devices	53
	11.5.2 Variable Pitch Fans	53
	11.5.3 Inverter Drives	54
	11.5.4 Eddy Current Couplings	54
	11.5.5 Switched Reluctance Drives	54
11.6	Frequency Inverters	54
	11.6.1 Sizing	54
	11.6.2 Motor Cooling	55
	11.6.3 Starting/Isolation	55
	11.6.4 Acoustic Noise	55
11.7	Switched Reluctance Drives	55
	11.7.1 Motor Cooling	56
	11.7.2 Starting/Isolation	56
11.8	Eddy Current Coupling	56
	11.8.1 Sizing	56
	11.8.2 Starting/Isolation	56
11.9	Multiple Speed Motors	56
11.10	Inlet Guide Vanes	57
11.11	Dampers	57
11.12	Variable Pitch Fans	58
11.13	Control System Interfacing/Communications	59
11.14	Location/Housing	59
11.15	Cabling	60
	11.15.1 Power Cables	60
	11.15.2 Control Signal Cables	61
11.16	Fuses	61
11.17	Power Factor Correction	61
11.18	Critical Speeds	61
11.19	Multiple Motors	62
11.20	Commissioning	62
11.21	Safety	62

---

<b>12. Maintenance</b>	<b>63</b>
12.1 Safety Checks	63
12.2 Monitoring	63
12.3 Belt Drives and Bearings	63
12.4 Filters	63
12.5 VSDs	63
12.6 Multiple Speed Motors	63
12.7 Inlet Guide Vanes, Disc Throttles and Dampers	64
12.8 Variable Pitch Fans	64

---

<b>13. Good Practice Recommendations</b>	<b>65</b>
--	-----------

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<b>14. Findings of a UMIST VAV research project (funded by EPSRC)</b>	<b>66</b>
14.1 Network Analysis	66
14.1.1 Duct Resistance Concept	66
14.1.2 Duct Size Implications	67
14.2 Idealised VAV Systems	67
14.2.1 Synchronous System	67
14.2.2 Asynchronous System	67
14.3 Potential Savings of a Synchronous VAV System	68
14.4 Fan Energy Savings with VAV Systems	69
14.5 Duct Loops	69
14.6 Refrigeration vs Fan	70
14.7 Pressure Independent Boxes	70

---

## FIGURES

---

Number	Title	Page
1	Centrifugal pump	5
2	Characteristics of one and two pump operation	7
3	Typical absorbed fan power	8
4	10% regulation of pump with steep curve	10
5	20% regulation of pump with steep curve	11
6	10% regulation of pump	12
7	20% regulation of pump	13
8	Flow meter installation	15
9	Heating pump energy savings	16
10	Chilled water pump energy savings	17
11	Eddy current coupling	18
12	PWM inverter	20
13	Switched reluctance drive	21
14	Variable pitch axial fan	24
15	Inlet guide vanes	24
16	Disc throttle	25
17	Dampers	25
18	VAV air-conditioning system	26
19	VAV system with DDC	27
20	Recirculation system air quality control	31
21	Full fresh air system quality control	32
22	Outside temperature reset ventilation control	33
23	Variable flow heating or chilled water system	35
24	Differential pressure control valve locations	38
25	Fan and system curves	66
26	Synchronous load distribution with 4 zones	67
27	Asynchronous load distribution with 4 zones on one floor	67
28	Fan operation curve and duct pressure distribution curve (with static pressure sensor close to fan)	68
29	Fan operation curve and duct pressure distribution curve (with static pressure sensor close to fan)	68
30	Fan operation curve and duct pressure distribution curve (with static pressure sensor close to index VAV terminal box)	68
31	Duct resistance network	69
32	Duct resistance layout of a duct loop VAV system	70
33	Installed flow characteristics of two typical VAV terminal units	70

## TABLES

---

Number	Title	Page
1	Control methods for fans	4
2	Efficiency of fan control methods	42
3	Efficiency of pump control methods	43
4	Capital costs	43
5	Calculation of ARR	47
6	Calculation of NPV	48

## GLOSSARY OF TERMS

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Title	Abbreviation
Alternating current	AC
Air handling unit	AHU
Accounting rate of return	ARR
Current source inverters	CSI
Direct current	DC
Discounted cash flow	DCF
Double inlet double width	DIDW
Eddy current couplings	ECC
Electro magnetic compatibility	EMC
Inlet guide vanes	IGV
Insulated gate bipolar transistors	IGBT
Multi speed motors	MSM
Net present value	NPV
Proportional plus integral	P&I
Pulse amplitude modulation	PAM
Proportional, integral and derivative	PID
Pulse width modulation	PWM
Residual current control devices	RCCDs
Radio frequency interference	RFI
Switched reluctance drive	SRD
Steel wire armour	SWA
Thermostatic radiator valve	TRV
Volumetric air valve	VAV
Variable speed drives	VSD
Voltage vector control inverter	VVC
Voltage vector inverter	VVI

## 1. INTRODUCTION

---

This General Information Report, produced under the Department of the Environment's (DOE) Energy Efficiency Best Practice programme, draws on the extensive experience of manufacturers, designers, installers and commissioning engineers to assist readers in the installation of reliable and energy efficient methods of variable flow control.

It has been developed primarily to support a series of presentations given at workshops jointly run by BRECSU (for DOE) and CIBSE to professional design engineers and design technicians. Minor changes have been made following feedback from delegates attending workshops in 1995. The workshops are to be continued in 1996.

All users must ensure that their use and interpretation of information contained in this guidance is in accordance with current legislation and practice.

- The aim of the Report is to increase the uptake of energy efficient methods of flow regulation and variable flow control in building services.
- The emphasis is on systems that are robust, and as simple as possible consistent with achieving economical operation.
- Building services are sized for peak loads and spend most their life operating well below full output.
- Typically 20% of full volume energy is required to move water and air at 50% of maximum flow.
- This provides significant opportunities for cost savings, from reductions in energy consumed, from longer equipment life, and from lower maintenance.
- It is estimated that around £850 million per annum is currently spent on the electricity consumed by alternating current (AC) electric motors driving fans and pumps in building services in the UK.
- Savings in electricity usage are of substantially greater environmental benefit than the equivalent savings in fossil fuel.
- Consumption of one kilowatt-hour of electricity releases approximately three times as much carbon dioxide into the atmosphere as one kilowatt-hour of fossil fuel.

### 1.1 Overall objectives

The main objectives are to enable the relevant technical personnel to:

- identify energy efficient and cost-effective applications of flow regulation and variable flow control
- select and specify the most suitable type of flow regulation and variable flow control for the application
- specify the most effective control strategy for the application
- engineer, install and commission the system to a high standard
- maintain the system for long-term energy efficient operation.

### 1.2 Scope

- This Report considers methods of flow regulation and variable flow control applicable to typical fan and pump applications in commercial buildings.
- These include heating, ventilation, air conditioning, cooling tower and condenser applications.
- Control of chillers has not been included due to the specialised nature of refrigeration plant.

### **1.3 Guidance**

- The guidance given includes best practice based at October 1994.
- Users must ensure that they conform with all current regulations.

### **1.4 Further information**

Please contact BRECSU for further information on matters related to energy in buildings.

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### **1.5 Acknowledgements**

This document has been developed under contract to BRECSU for the DOE by Graham Smith of Birling Systems Design Ltd.

Thanks are due to Paul Compton, Colt Group; David Morris, Consultant; Tony Sheldrake, Danfoss; Mike Steddy, Landis & Gyr; and Nick Skemp, BDP – members of the advisory group chaired by Colin Ashford.

If you have any feedback on the report/workshops, please contact: Colin J Ashford, BRECSU, Building Research Establishment, Garston, Watford WD2 7JR. Fax: 01923 664097.

## 2. FAN AND PUMP LAWS

---

### 2.1 Fan Laws

For a given system in which the pressure loss increases by the square of the flow and without change of density:

- the inlet volume varies in proportion to the speed of the fan
- the fan total pressure and static pressure varies as the square of the fan speed
- the air power (total or static) and the impeller power varies as the cube of the fan speed.

For changes in density:

- the fan total power, the static pressure and the fan power all vary directly as the mass per unit volume of the air which, in turn, varies directly as the barometric pressure and inversely as the absolute temperature.

For geometrically similar airways and fans operating at a constant speed and efficiency with constant air density:

- the inlet volume varies as the cube of the fan size
- the total and static fan pressures vary as the square of the fan size
- the air power (total and static) and the impeller power vary as the fifth power of the fan size.

The first three laws are of particular interest for variable flow control. It should be noted that a volumetric air valve (VAV) system has modulating terminal units which vary the flow according to local demand. These require an inlet pressure within a certain range to operate. The system therefore does not exactly follow the first law above.

### 2.2 Pump Laws

The pump laws state that with a constant impeller diameter:

- volume varies in proportion to speed
- pressure varies as the square of the speed
- absorbed power varies as the cube of the speed.

For a change in impeller diameter at constant speed:

- volume varies as the cube of the diameter
- pressure varies as the square of the diameter
- absorbed power varies as the fifth power of the diameter.

### 3. VARIABLE FLOW CONTROL METHODS

#### 3.1 Fans

- A wide variety of fans is available for building services applications.
- The application often dictates the type of fan used.
- Fan efficiencies vary considerably.
- Selection of an energy efficient fan in association with variable flow control should be considered wherever possible.

Fan	Application	Control Method		Comments
Centrifugal	Air handling units (AHUs) Forced draft cooling towers High pressure/flow ratio applications	VSD	PWM inverter	Most often used
			SRD	Special motor required
			ECC	Robust, no harmonics
		MSM		Limited application
		IGV		Not recommended
		Disc throttle		Only recommended for limited flow turndown
		Dampers		Not recommended
Mixed flow	Large AHUs, VAV medium pressure/flow ratio applications	Generally as centrifugal		As centrifugal (No disc throttle)
Axial	Large AHUs, VAV Forced draft cooling towers Low pressure/flow ratio applications Smoke extract	Variable pitch		Electro pneumatic actuation requires caution. Allows constant pressure variable flow
		VSD		Good potential
		MSM		Limited application
		IGV		Not recommended
		Dampers		Not recommended
Propeller *	Non ducted applications, Condensers, Induced draft cooling towers	MSM		Most often used
		PWM inverter		Good potential
Cross and tangential flow*	Terminal units Low pressure applications	MSM		Most often used
		PWM inverter		Good potential, also multiple motors
VSD - Variable speed drives, PWM - Pulse width modulation, SRD - Switched reluctance drive, ECC - Eddy current couplings, IGV - Inlet guide vanes, MSM - Multi speed motors      *Poor overall fan efficiency.				

Table 1 Control methods for fans

- Fixed pitch axial fans - blades are normally adjustable - efficient volume setting.
- Variable pitch axial fans enable constant static pressure to be maintained at low volumes in an energy efficient manner.
- Variable pitch axial fans require stall protection.
- Cross and tangential flow fans are designed to operate at particular speeds and do not follow fan laws outside design speeds.
- Brushless direct current (DC) motors are also available for cross and tangential flow fans.

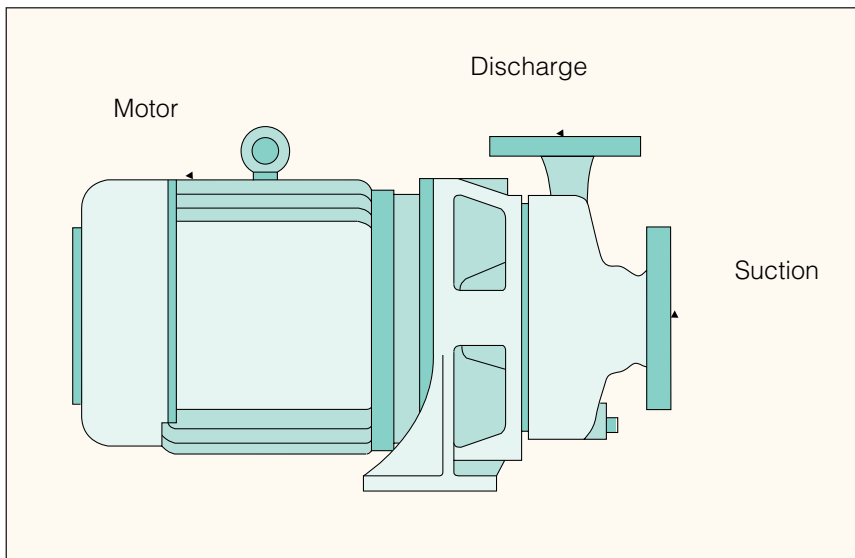
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### 3.2 Pumps

- Centrifugal pumps – wide range of flow and pressure characteristics.
- Suitable almost all non-domestic building services applications.
- Other pumps not considered.
- Usually single stage.

Volume control methods:

- variable speed drives (VSDs)
- in-built VSDs
- regulation via manual regulating valves
- throttling valves or bypass valves.



**Figure 1 Centrifugal pump**

### 3.3 Belt and Direct Drives

- Smaller pumps and fans are normally direct drive and larger pumps and fans belt drive.
- Small direct drive pumps and fans are often supplied with multiple speed motors.

#### 3.3.1 Belt Drives

Benefits

- Speed can be altered, via a change of pulleys, to match the characteristic curve to the application.
- Reduced noise transmission.
- Allows the motor to be located outside the airstream in AHUs. This eliminates heat gain to the air from the motor.
- Allows permanent connection of a standby fan motor.

Drawbacks

- Increased energy consumption.
- Regular maintenance is required.
- Belt losses normally 5 to 10%, and can be up to 15% for small drives.
- Belt losses greater when poorly maintained.
- Belt guard additional losses from windage.
- Additional losses from permanently connected standby motors.
- Limited ranged pulleys.

#### Developments

- Cogged V-Belts can be used as a direct replacement and typically give around 3% improvement in drive efficiency.
- Flat or synchronous belts are typically 97 to 99% efficient.
- Flat and synchronous belts do not require maintenance.
- Flat belts have low noise and small slip.
- Flat belts require special pulleys which are low cost.
- Flat belt tension is set during commissioning and remains essentially constant for belt lifetime.
- Synchronous belts have zero slip, can be noisy and damaged by shock loads.
- Synchronous belts require special toothed pulleys which can be expensive.

#### **3.3.2 Direct Drives**

##### Benefits

- No drive losses.
- Motor and fan/pump assembly can be more compact.

##### Drawbacks

- No provision to alter speed unless VSDs or MSMs.
- MSM coarse speed adjustment.
- More direct route for noise transmission.
- Motor heat gain not easily dissociated from air streams in some AHUs.
- Standby units are not normally available.
- Condensation protection required for some chilled water pumps.

### 3.4 Shared Duty and Standby

- AHU fans normally have permanently connected standby motors.
- Pumps are normally installed in pairs as a duty/standby.
- Two shared duty pumps can give capital savings and provide around 70% flow if one fails.
- Shared duty fans are possible but are less likely to be cost-effective.
- Capital cost savings include motors, wiring, VSDs, etc.
- Pump sizes will also be reduced.
- Space savings may result with fans.
- Non-return valves or dampers are required.
- Additional pressure losses of non return devices must be evaluated.
- Closed loop control is necessary to ensure that the working pump, or fan, increases speed to provide required flow (up to maximum available) in the event of failure.

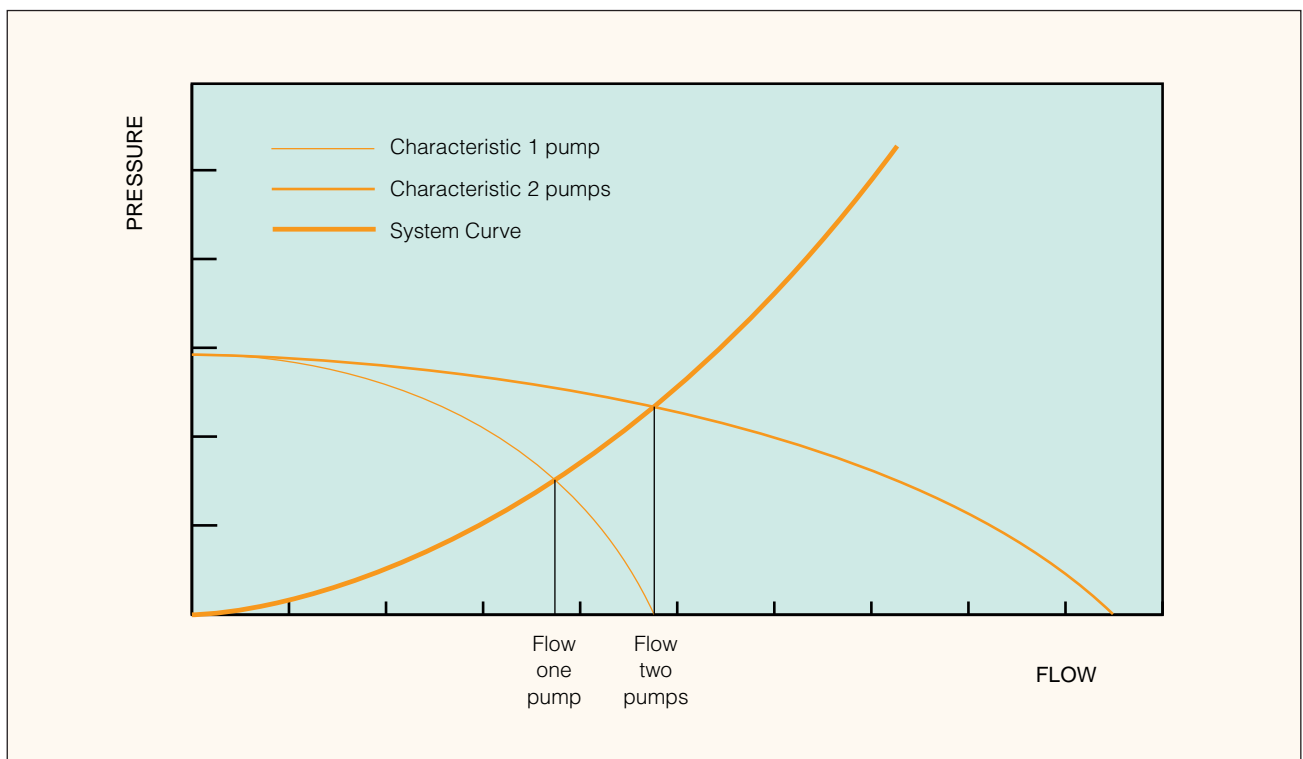
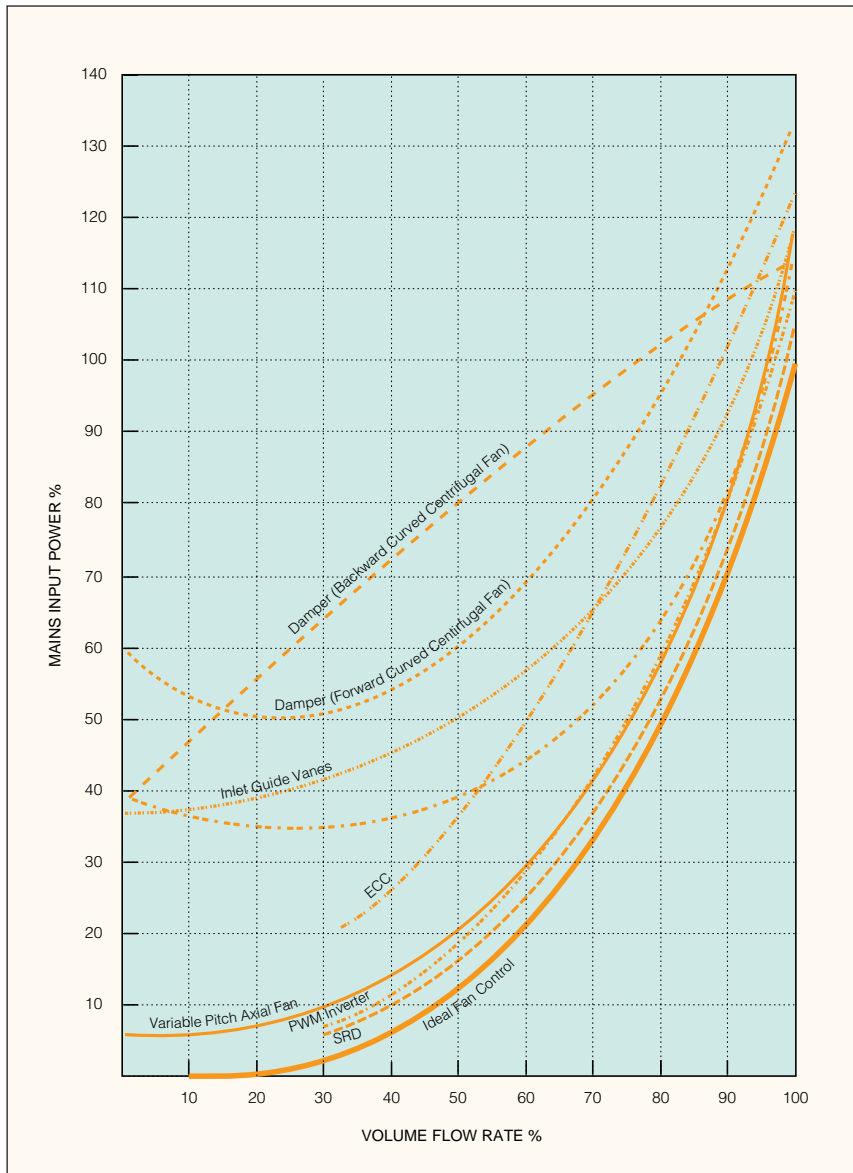


Figure 2 Characteristics of one and two pump operation

#### 4. COMPARATIVE EFFICIENCIES OF VARIABLE FLOW CONTROL METHODS



**Figure 3 Typical absorbed fan power**

- Substantial power savings are obtainable by utilising one of the more efficient control methods.
- PWM frequency inverters, SRD or variable pitch axial fan most efficient.
- Mechanical methods such as IGV damper control, etc far less efficient.
- Ideal fan control 100% power at maximum volume.
- The eddy current coupling is the least efficient variable speed drive system.
- SRD most efficient, particularly at full speed.
- Disc throttle provides control to zero flow.
- Pump comparisons similar with PWM frequency inverters and SRD.
- High efficiency motors (where applicable) slightly reduced savings with inverters at low speeds.

## 5. SYSTEM REGULATION

---

### 5.1 Traditional Methods

- Fans and pumps are normally selected with a safety factor of around 10% surplus head pressure at design flow rates and/or 15% additional flow at design pressure loss.
- The fan or pump with the next higher performance curve is then selected from the manufacturers' data.
- Fans and pumps normally at least 15 to 20% oversized.
- Many systems fans and pumps considerably oversized.
- Poor power factor where motors oversized.

First Stage - Match fan or pump to system as follows:

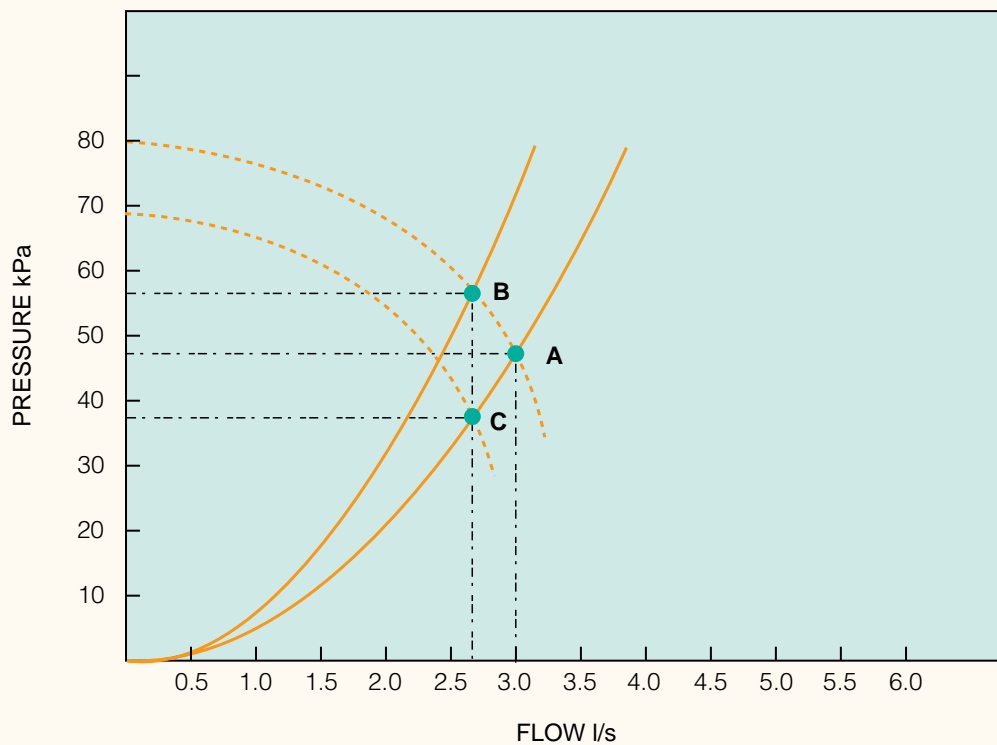
- belt drives - change of pulleys normally allows the duty to be matched to within 10%
- additional belt losses
- smaller pump impellers - slight reduction in pump efficiency
- MSMs - coarse adjustment of fan/pump characteristic
- axial fan - blade adjustment
- often not done due to lack of time or components.

Second Stage - Regulate system as follows:

- system resistance increased until flow rate is reduced via regulating valves or dampers
- inherently inefficient due to increased system resistance.

### 5.2 Regulation via VSDs

- Matches fan or pump to system.
- Very rapid results.
- Accurate setting of speeds and flow.
- Additional flexibility - maximum demand control - reduce flows.
- Ease of resetting to match flow to actual loads.
- Cost savings for regulating valves or dampers.
- In unlikely event of exact match of pump/fan to system, energy penalty approximately 10% PWM inverter, 5% SRD.
- Often will dramatically reduce energy consumption.
- Savings normally as soon as 5% flow regulation.
- 20 to 50% savings possible with 10 to 20% regulation.
- Normally (but not always) operate nearer point of maximum efficiency compared with conventional flow regulation.
- Near unity power factor at all flows with suitable VSD.



**Figure 4 10% Regulation of pump with steep curve**

Figure 4 shows relatively steep pump curves (dotted lines) and corresponding system curves (solid line). The intersection point A is the operating point when the system is unregulated giving a flow of 3.0 l/s at a pump head of 48.4 kPa. If the desired flow rate is 2.7 l/s then the system would normally be regulated via a regulating valve to alter the system curve. The operating point would then be B giving 2.7 l/s at 57.7 kPa. If a VSD is used to reduce the pump curve, rather than increase system resistance, the operating point will be at C giving 2.7 l/s at only 38.6 kPa.

The energy used is as follows:

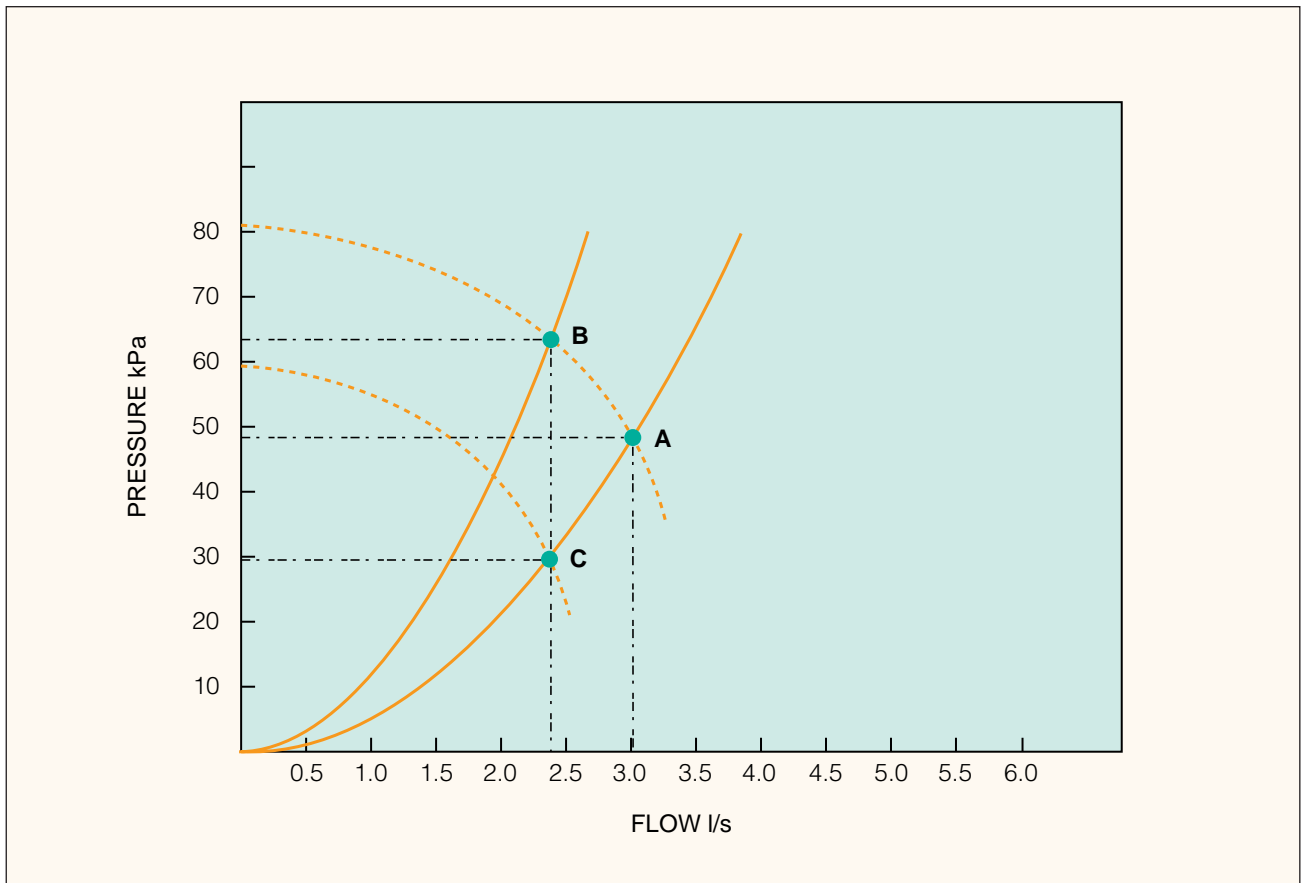
$$\begin{aligned}
 \text{Energy at point A} &= \text{Flow} \times \text{Pump head} \div \text{Pump efficiency} \\
 &= 3 \times 48.4 \div 0.78 \\
 &= 186 \text{ W}
 \end{aligned}$$

$$\begin{aligned}
 \text{Energy at point B} &= \text{Flow} \times \text{Pump head} \div \text{Pump efficiency} \\
 &= 2.7 \times 57.7 \div 0.8 \\
 &= 195 \text{ W}
 \end{aligned}$$

$$\begin{aligned}
 \text{Energy at point C} &= \text{Flow} \times \text{Pump head} \div (\text{Pump efficiency} \times \text{VSD efficiency}) \\
 &= 2.7 \times 38.6 \div (0.78 \times 0.92) \\
 &= 145 \text{ W}
 \end{aligned}$$

$$\begin{aligned}
 \text{Energy saved} &= ((B - C) \div B) \times 100\% \\
 &= ((195 - 145) \div 195) \times 100\% \\
 &= \mathbf{25.6\%}
 \end{aligned}$$

Therefore, over a quarter of the energy is saved by using a VSD for 10% flow regulation compared with a regulating valve!



**Figure 5 20% Regulation of pump with steep curve**

Figure 5 shows the same pump and system curve as in figure 4, in this instance the desired flow is 2.4 l/s.

The energy used is as follows:

$$\begin{aligned}
 \text{Energy at point A} &= \text{Flow} \times \text{Pump head} \div \text{Pump efficiency} \\
 &= 3 \times 48.4 \div 0.78 \\
 &= 186 \text{ W}
 \end{aligned}$$

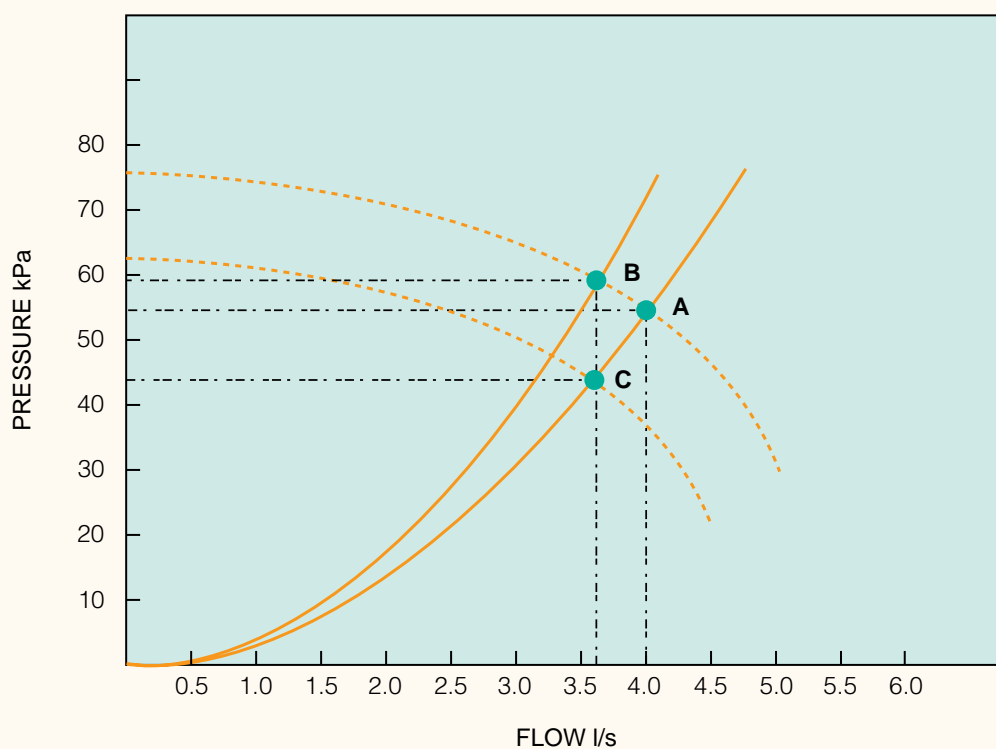
$$\begin{aligned}
 \text{Energy at point B} &= \text{Flow} \times \text{Pump head} \div \text{Pump efficiency} \\
 &= 2.4 \times 63.5 \div 0.78 \\
 &= 195 \text{ W}
 \end{aligned}$$

$$\begin{aligned}
 \text{Energy at point C} &= \text{Flow} \times \text{Pump head} \div (\text{Pump efficiency} \times \text{VSD efficiency}) \\
 &= 2.4 \times 29.9 \div (0.78 \times 0.92) \\
 &= 102 \text{ W}
 \end{aligned}$$

$$\begin{aligned}
 \text{Energy saved} &= ((B-C) \div B) \times 100\% \\
 &= ((195 - 102) \div 195) \times 100\% \\
 &= \mathbf{47.7\%}
 \end{aligned}$$

Therefore, nearly half of the energy is saved by using a VSD for 20% flow regulation compared with a regulating valve!

The savings illustrated in figures 4 and 5 are reasonably high because the pump curve is relatively steep. However, the curve has been taken straight from a typical manufacturer's details and these savings are not untypical.



**Figure 6 10% Regulation of pump**

Figure 6 shows a flatter pump curve, for a 10% reduction in flow the energy used is as follows:

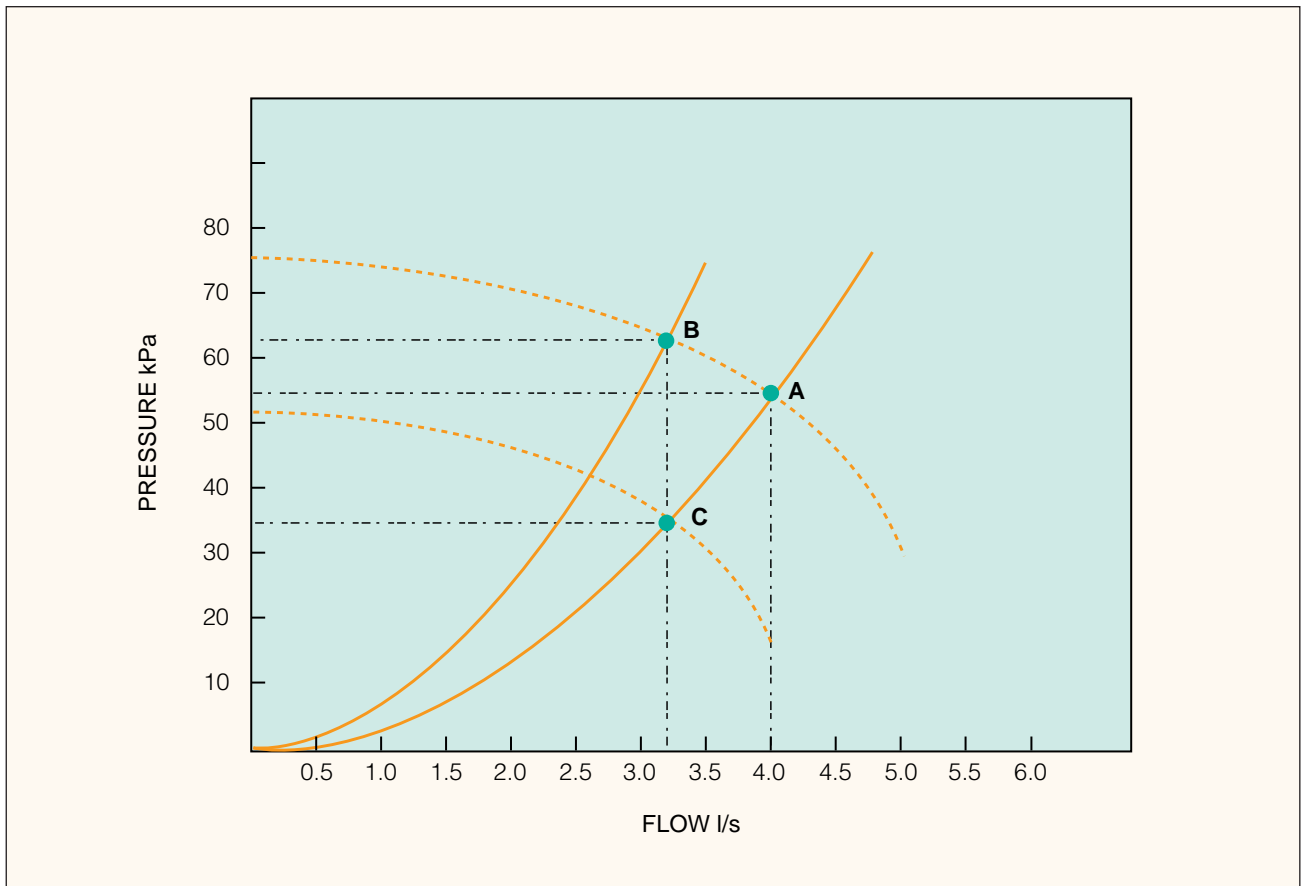
$$\begin{aligned}
 \text{Energy at point A} &= \text{Flow} \times \text{Pump head} \div \text{Pump efficiency} \\
 &= 4 \times 54.6 \div 0.8 \\
 &= 273 \text{ W}
 \end{aligned}$$

$$\begin{aligned}
 \text{Energy at point B} &= \text{Flow} \times \text{Pump head} \div \text{Pump efficiency} \\
 &= 3.6 \times 59.2 \div 0.8 \\
 &= 266 \text{ W}
 \end{aligned}$$

$$\begin{aligned}
 \text{Energy at point C} &= \text{Flow} \times \text{Pump head} \div (\text{Pump efficiency} \times \text{VSD efficiency}) \\
 &= 3.6 \times 43.8 \div (0.78 \times 0.92) \\
 &= 214 \text{ W}
 \end{aligned}$$

$$\begin{aligned}
 \text{Energy saved} &= ((B - C) \div B) \times 100\% \\
 &= ((266 - 214) \div 266) \times 100\% \\
 &= \mathbf{19.5\%}
 \end{aligned}$$

Therefore, even with a flatter pump curve nearly 20% of the energy is saved by using a VSD for 10% flow regulation compared with a regulating valve!



**Figure 7 20% Regulation of pump**

Figure 7 shows the flatter pump curve as in figure 6, for a 20% reduction in flow the energy used is as follows:

$$\begin{aligned}
 \text{Energy at point A} &= \text{Flow} \times \text{Pump head} \div \text{Pump efficiency} \\
 &= 4 \times 54.6 \div 0.8 \\
 &= 273 \text{ W}
 \end{aligned}$$

$$\begin{aligned}
 \text{Energy at point B} &= \text{Flow} \times \text{Pump head} \div \text{Pump efficiency} \\
 &= 3.2 \times 62.7 \div 0.78 \\
 &= 257 \text{ W}
 \end{aligned}$$

$$\begin{aligned}
 \text{Energy at point C} &= \text{Flow} \times \text{Pump head} \div (\text{Pump efficiency} \times \text{VSD efficiency}) \\
 &= 3.2 \times 34.7 \div (0.8 \times 0.9) \\
 &= 154 \text{ W}
 \end{aligned}$$

$$\begin{aligned}
 \text{Energy saved} &= ((B - C) \div B) \times 100\% \\
 &= ((257 - 154) \div 257) \times 100\% \\
 &= \mathbf{40\%}
 \end{aligned}$$

### 5.3 Regulation Conclusions

- Even with a flatter pump curve 40% of the energy is saved by using a VSD for 20% flow regulation compared with a regulating valve!
- It is possible that if ideal impeller sizes were available similar savings could be achieved, although there would be some reduction in pump efficiency due to reduction in impeller size.
- However, it is unlikely that an ideal size would be available, and even more unlikely that it would ever be fitted.
- With belt driven pumps or fans, exact matching of speed via belt drives would reduce energy consumption. However, there would be additional belt losses and again exact matching is unlikely in practice.
- For general guidance, unless the pump or fan curves are exceptionally flat, it should be safe to assume around 20% saving for a 10% regulation of flow and 40% for a 20% regulation of flow.
- These savings make the use of VSDs viable purely for regulation in many instances.

### 5.4 Existing Installations

- Evaluate current use and loads.
- Compare original specification and commissioning figures with current use.
- Check amount of manual regulation via valves and dampers.
- Check for noisy diffusers - high velocities.
- Minimum air changes and fresh air content must be considered.
- Additional savings can result from reduced heating and cooling loads with reduced flows.
- Consider modern diffusers for lower air velocities to prevent cold air dumping.

## 5.5 Water Flow Measurement

- Flow measurement valves must have straight pipework upstream and downstream.
- Minimum 10 pipe diameters upstream and 5 diameters downstream.
- Significantly reduced lengths - can lead to totally misleading readings.
- Relocate flow measurement valves.
- Use portable ultrasonic meters for comparison.
- Large systems magnetic flow meters or vortex shedding meters more accurate than orifice devices.

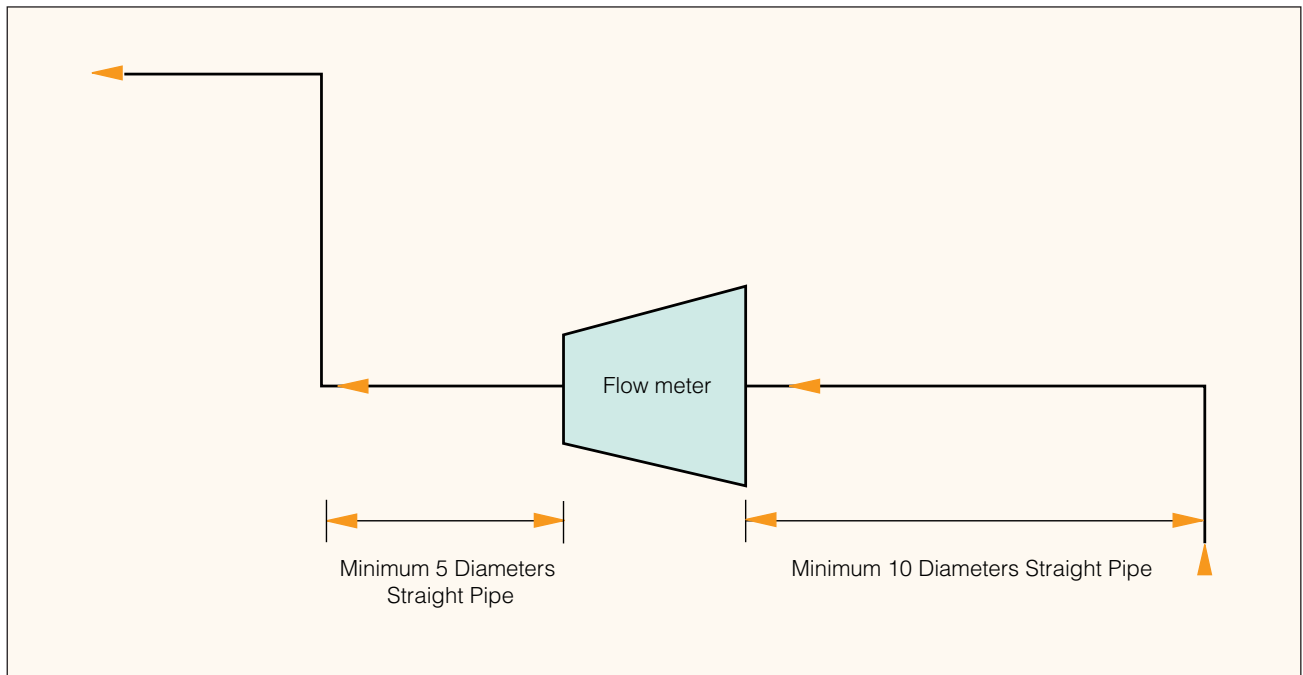


Figure 8 Flow meter installation

## 5.6 Axial Fans

- Adjust blade angle to match duty if possible.
- Much more difficult than reset of VSD speed.
- No capital expenditure.

## 6. VARIABLE FLOW CONTROL ENERGY SAVINGS

- Instantaneous flow rate is dependent on system load.
- Maximum flow rate is necessary for only a small proportion of the time.
- Effective control with respect to system load is essential.

### 6.1 Office Building, Heating Pumps

Hour	1	2	3	4	5	6	7	8	9	10	Average
Flow Rate %	100	90	70	55	40	30	30	32	38	45	53.0
Energy Consumption %	110.0	82.9	42.3	23.6	13.4	9.7	9.7	10.3	12.5	16.1	33.1
Energy Saving %	-10.0	17.1	57.7	76.4	86.6	90.3	90.3	89.7	87.5	83.9	66.9

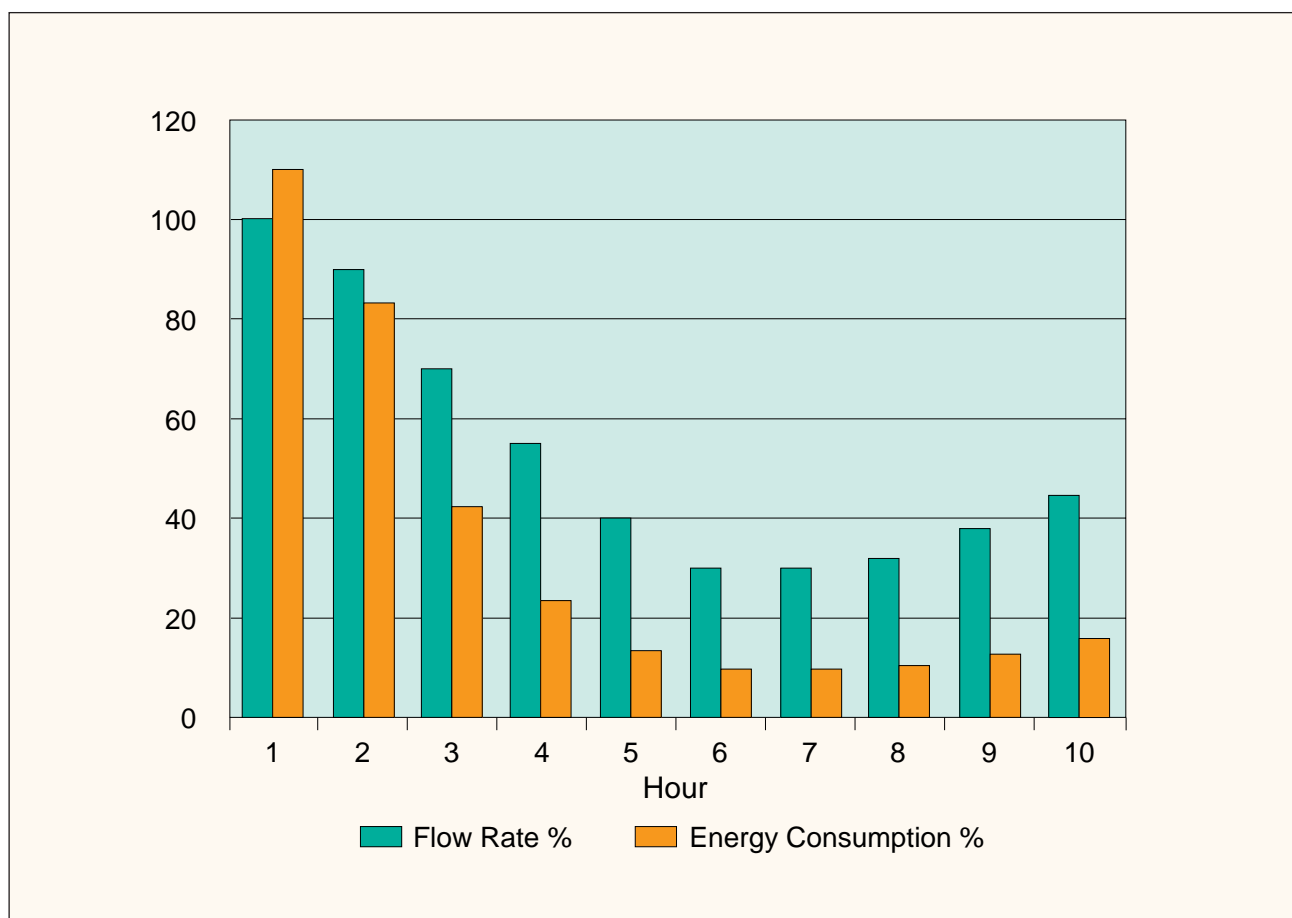
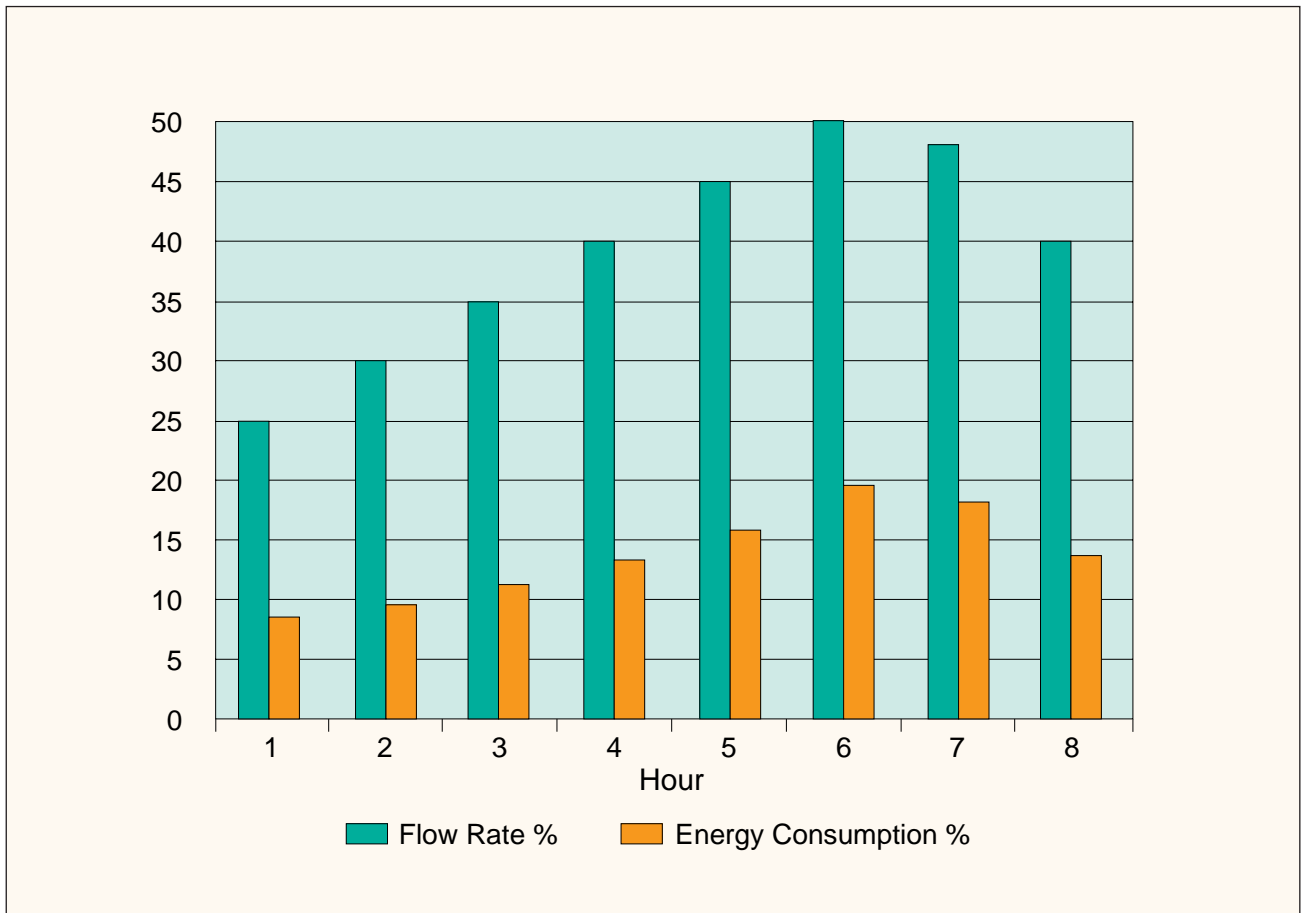


Figure 9 Heating pump energy savings (and tabulated above)

- Figure 9 shows the typical operation of a heating pump in an office building.
- Full flow is usually only required on boost.
- Average flow rate is 53% and average energy is 33.1%.
- Energy saving of 66.9%.
- These savings are representative of those achievable over a full heating season.
- With a pump consuming 15 kW at full load, savings of approximately £1200 pa would be obtained based on 1994 electricity costs.
- Typical simple payback would be 2.1 years.

## 6.2 Airport Building, Chilled Water Pumps

Hour	1	2	3	4	5	6	7	8	Average
Flow Rate %	25	30	35	40	45	50	48	40	39.1
Energy Consumption %	8.6	9.7	11.3	13.4	16.1	19.5	18.1	13.4	13.8
Energy Saving %	91.4	90.3	88.7	86.6	83.9	80.5	81.9	86.6	86.2



**Figure 10 Chilled water pump energy savings (and tabulated above)**

- Figure 10 shows the typical operation of a chilled water pump in an airport terminal building.
- Average flow rate is 39% and average energy is 13.8 %.
- Energy saving of 86.2%.
- These savings are representative of those achievable over a typical summer.
- Full flow is hardly ever required.
- With a pump consuming 15 kW at full load, savings of approximately £900 pa would be obtained based on 1994 electricity costs.
- Savings are less than the heating pump example due to reduced number of hours run.
- Typical simple payback would be 2.8 years.
- Savings with chilled water pumps are more varied than heating pumps as some run during the summer only but others are required all year and have very low loads for much of the time.
- Very rapid paybacks are possible where there are long periods of operation at low load.

## 7. VARIABLE SPEED DRIVES

### 7.1 Eddy Current Couplings

The eddy current coupling is an electro-magnetic coupling which fits between a standard AC induction motor and the fan or pump.

#### Advantages

- Well proven and reliable - used for over 25 years.
- High torques at low speed - not normally required.
- No harmonics generated.
- Bypass of recent controllers for full speed operation possible.

#### Disadvantages

- Limited to 90 kW for building services applications.
- Torque dependent on coupling slippage necessary to generate magnetic fluxes/eddy currents.
- Maximum output speed less than motor speed due to coupling slippage.
- Typical maximum output speed 1300 to 1350 rpm with 1450 rpm input speed.
- Additional space required.
- 'Piggy back' mountings to save in-line space require belt drives.
- Bypass of the coupling in the event of failure not possible.
- Controller less sophisticated than typical frequency inverter.
- Typically settings - acceleration/deceleration rates and torque limit.
- Maximum, minimum and avoidable speeds not normally available.
- Additional heat gain if motor is located in the airstream.

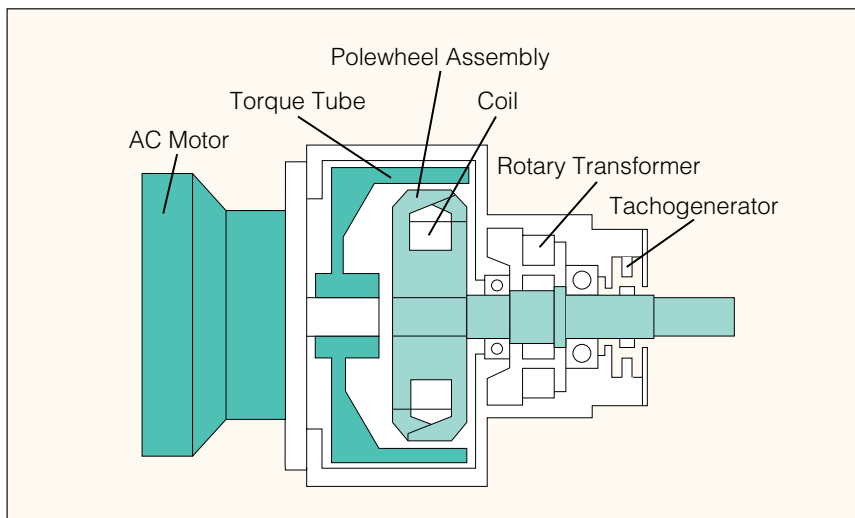


Figure 11 Eddy current coupling

### 7.2 Inverters

Most popular method for fan and pump speed control due to efficiency and recent reductions in relative costs.

#### Advantages

- Easier for retrofit installations.
- Standard motor and drive arrangements used.
- Can be bypassed with an additional starter.
- Motor starters not required.
- Near unity power factor.

- Sophisticated controllers allowing many factors such as maximum/minimum speeds, maximum acceleration rates, etc to be programmed.
- Most controllers allow resonant speeds to be bypassed.
- Reduced motor wiring compared with star/delta starting of larger motors.
- Limited starting current for 'soft start'.
- Avoids the need for a complex phased start at switch on in large buildings.
- One inverter can be used for more than one motor in some circumstances.
- Modern inverters are now considered to be very reliable.
- Around 15 years use in building services.

#### Disadvantages

- Motor output had to be derated with older design of inverters.
- Normally matched to motor frame size.
- Electromagnetic compatibility (EMC) including harmonics must be adequately considered during the design process.
- Noise from motor if a low carrier frequency is used. (Modern devices tend to use higher frequencies to avoid this problem.)
- Older units may require power supply contactors for isolation. Modern units conventional motor isolators OK.

#### Main types of inverter

- Current Source Inverters (CSI).
- Pulse Amplitude Modulation (PAM).
- Pulse Width Modulation (PWM).

#### **7.2.1 Current Source Inverters**

CSIs are not generally recommended for building services applications.

#### Advantages

- Low costs.
- Simplicity.
- Ability to feed power back into the mains.

#### Disadvantages

- Controlled rectifier - greater mains disturbance - harmonics.
- Lower efficiency of operation.
- Voltage wave - substantial spikes.
- Power factor varies according to load.
- Not suitable for no load operation.
- Not suitable for multi-motor applications.
- Physically larger than other types of inverter.

#### **7.2.2 Pulse Amplitude Modulation Inverters**

Uncontrolled rectifiers and 18 pulse inverter outputs are recommended for PAM inverters. Modern PWM inverters normally better.

- DC voltage varies in conjunction with frequency.
- Voltage varied in steps.
- Current an approximation of a sine wave.
- Six pulse inverter outputs poor waveform.
- 18 pulse inverter outputs improved waveform.
- Controlled rectifier - greater mains disturbance - harmonics.
- Uncontrolled rectifier available - near unity power factor at all loads.

### 7.2.3 Pulse Width Modulation Inverters

Modern PWM inverters with insulated gate bipolar transistors (IGBTs) generally recommended over other forms of inverter.

- Amplitude of voltage not controlled.
- Voltage variation achieved by rapidly switching on and off.
- Older PWM inverters - bipolar transistors maximum switching frequency of 2 to 5 kHz.
- Now IGBTs allow switching frequencies up to 20 kHz.
- IGBTs have much improved switching performance.
- Current waveform is much nearer the ideal sine wave.
- Quieter operation.
- More efficient due to reduced switching losses and a better wave-form.
- No motor oversizing is necessary with IGBTs.
- 10% motor derating with bipolar transistors.
- Uncontrolled rectifiers - higher connected loads.
- Near unity power factors at all loads with suitable DC link filtering.

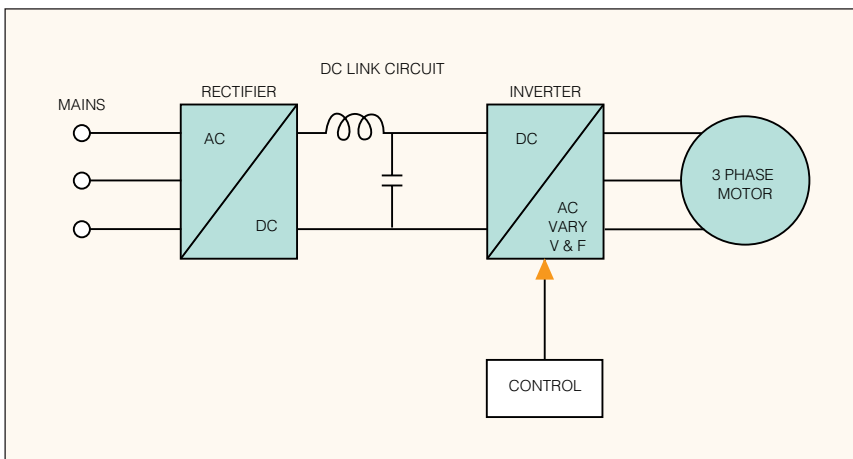


Figure 12 PWM inverter

### 7.2.4 Voltage Vector Control Inverter

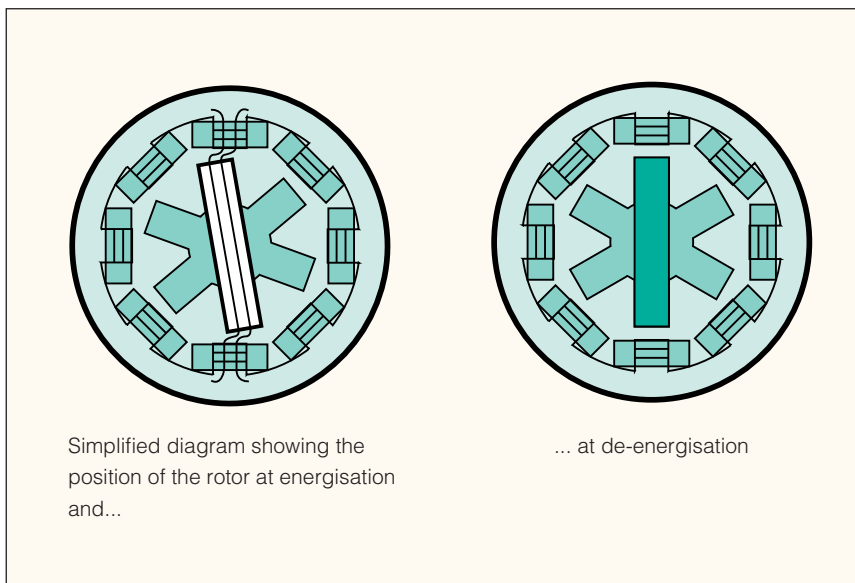
- VVC Inverter is a modified PWM inverter.
- Voltage and switching frequency varies during the output AC cycle.
- Only available from one manufacturer at present.
- Claimed slightly more efficient than PWM inverter.
- Claimed better speed control.
- Recommended where cost-effective.

### 7.2.5 Flux Vector Control Inverter

- Derivation of the PWM inverter.
- Also known as space or field vector.
- Takes account of the varying motor flux and torque as the rotor rotates.
- Feedback of rotor position and three phase current are required.
- The drive must also be matched to the performance characteristics of the motor.
- Very accurate motor control with rapid response to input signals.
- Very complicated and expensive.
- Use cannot normally be justified for building services applications.

### 7.3 Switched Reluctance Drives

- Special brushless motor.
- Greater number of stator poles than rotor poles.
- Motor is inherently simple and reliable.
- Output to the motor is in DC pulses.
- Motor speed and torque controlled by timing and width of current pulses.
- Current SRD controllers use IGBTs as per most recent inverters.
- SRD controller must be compatible with the motor.
- Components of the SRD controller are similar to an inverter but the circuit and control strategy are different.
- Design and development has slowed general introduction.



**Figure 13 Switched reluctance drive**

#### Advantages

- Motor starters not required.
- Near unity power factor.
- Sophisticated controllers - maximum/minimum speeds, maximum acceleration rates etc.
- Available starting torques higher than frequency inverter controlled motors.
- Limited starting current for 'soft start'.
- Avoids the need for complex phased start up at switch on in large buildings.

#### Disadvantages

- EMC including harmonics must be adequately considered during the design process.
- Special motor and controller required.
- Higher motor noise although reduced on more recent motors.
- 7 core power and 6 core control motor connection required.
- Number of suppliers limited at present.
- Maximum motor size limited to 75 kW at present.
- Cannot be bypassed for full speed operation in the event of controller failure.
- Avoidable speeds not currently available.

## 7.4 Multi Speed Motors

- Used for small multi-speed pumps.
- Fan applications such as fan coil units.
- Normally two or three speeds.
- Two speed motors are standard induction motors with a 'tapped' winding.
- Three speeds common on pumps.
- Four speed motors are available.
- Three and four speed motors have additional windings - up to 8 poles.
- 3000 rpm two pole to 750 rpm as eight pole configuration.
- Small MSMs such as on domestic heating pumps use switched series resistances to change speed.

### Advantages

- Simple and low cost.
- No harmonics or radio frequency interference (RFI) generated.

### Disadvantages

- Special motor required, although commonly available.
- Coarse steps between speeds.
- Poor power factor at low speeds.
- Normally only available in fractional kW sizes.
- Some units have only local speed selection.

## 7.5 Variable Voltage

Two main types are available, electronic and variable auto transformer.

### 7.5.1 Electronic Variable Voltage VSDs

- Available in the UK from several suppliers.
- Electronically much simpler than an inverter.
- Modifies the waveform via phase angle control thyristors for a variable voltage output.
- Can be used for small AHUs, terminal units and small pumps with in-built VSDs.

### Advantages

- Normally lower cost than inverters.

### Disadvantages

- Efficiency not as good as inverters below 80% flow.
- Special motors matched to the controller have to be used.
- Often external rotor motors for cooling.
- High levels of harmonics reflected back into mains supply.

Only recommended for small pumps with in-built VSDs - not considered for any other use in remainder of the workshop.

### 7.5.2 Variable Auto Transformer VSDs

### Advantages

- No mains harmonics and RFI problems.

### Disadvantages

- More costly than electronic variable voltage VSDs.

Use is not considered further due to restricted advantages and availability.

## **7.6 DC VSDs**

- Commonly used for industrial applications.

### Advantages

- Accuracy of speed control.
- High starting torques.
- Efficiency of brushless DC drives

### Disadvantages

- Additional size.
- Weight.
- Capital costs.
- Maintenance costs.

Use is not considered further due to restricted advantages and costs.

## 8. MECHANICAL VARIABLE FLOW CONTROLS

### 8.1 Variable Pitch Axial Fans

- Flow controlled via variable pitch blades.
- Pitch modulated via pneumatic, electro-pneumatic or electric-actuator.

#### Advantages

- No harmonics or RFI generated.
- No special drives/controllers required.
- Static pressure can be maintained at low volumes.
- Control down to very low volumes possible.
- Parallel or series configurations possible.

#### Disadvantages

- Pneumatic supply often required.
- Miniature compressors for electro-pneumatic operation without moisture removal can cause control problems.
- Accuracy and hysteresis can be poor with electro-pneumatic operation.
- Additional maintenance required, particularly if pneumatic or electro-pneumatic control is used.
- Complex hub mechanics reduce reliability and increase maintenance downtime.
- Special fan assembly, may require additional length.
- Slow response time often used to limit wear on linkages.
- Linkage is in the airstream and can be adversely affected by humidifier and dewpoint air.
- Fan stall can occur when operated at an unsuitable point on characteristic curve.
- Great care needed in matching fan selection to full range of load to avoid stall.
- Repeated stall occurrences can cause fan blades to shear.

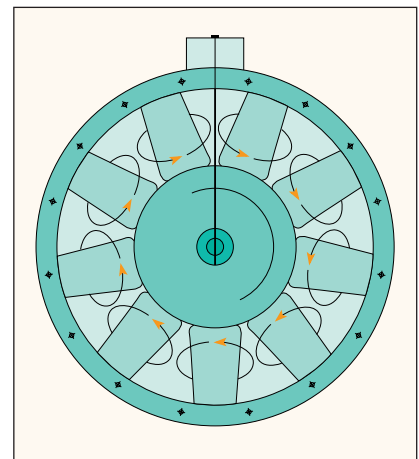


Figure 14 Variable pitch axial fan

### 8.2 Inlet Guide Vanes

IGVs can be used with centrifugal, mixed flow and axial fans although energy efficiency varies according to application.

#### Advantages

- No harmonics or RFI generated.
- No special drives/controllers required.

#### Disadvantages

- Poorer reliability.
- Additional maintenance required.
- Pressure loss across vanes.
- Additional noise at low volumes.
- Flow turndown limited.
- Often need high pressure pneumatic ram actuator due to high torques.
- Flow potentially unstable below 30% of maximum.
- Two IGVs with complex linkage required for double inlet double width (DIDW) fans.
- Regular maintenance necessary for reliable operation.

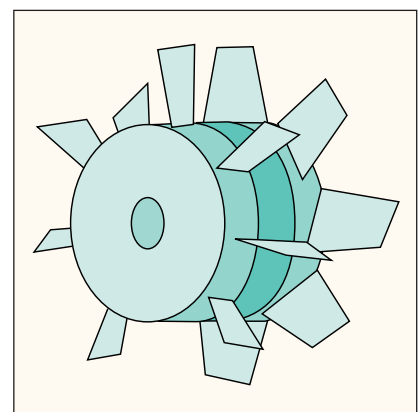


Figure 15 Inlet guide vanes

### 8.3 Disc Throttles

A disc throttle can only be applied to a centrifugal fan, where it alters the effective width of the impeller.

#### Advantages

- No harmonics generated.
- No special drives/controllers required.
- Flow turndown to very low volumes possible.
- DIDW linkage less complex than IGV.

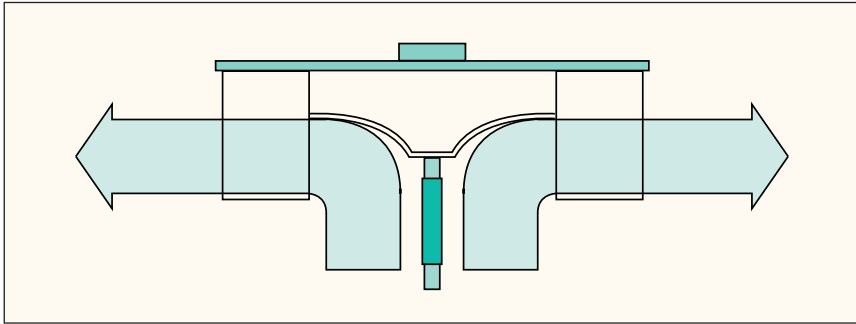


Figure 16 Disc throttle

#### Disadvantages

- Pressure loss - although less than IGV.
- Two disc throttles with a linkage required for DIDW fans.
- Regular maintenance necessary for reliable operation.

### 8.4 Dampers

Static dampers are used for overall flow regulation and proportional balancing. Modulating dampers are rarely used for modulating flow control except in mixing applications in AHUs. Opposed blade dampers recommended for variable flow applications as inherently lower pressure loss for correct authority.

#### Advantages

- No harmonics or RFI generated
- No special drives/controllers required.
- Flow turndown to very low volumes possible.
- Efficient control where used in conjunction with fan control such as VAV boxes.

#### Disadvantages

- Additional maintenance required.
- Sizing required for control authority.
- Additional pressure loss.
- Very inefficient as only form of variable flow control.

### 8.5 Regulating Valves

- Regulate flow in circuits by increasing the pressure loss.
- Proportional balancing of branches of circuits.
- Overall pump regulation to operate at its design flow.
- Regulation inefficient compared with reducing pump speed.

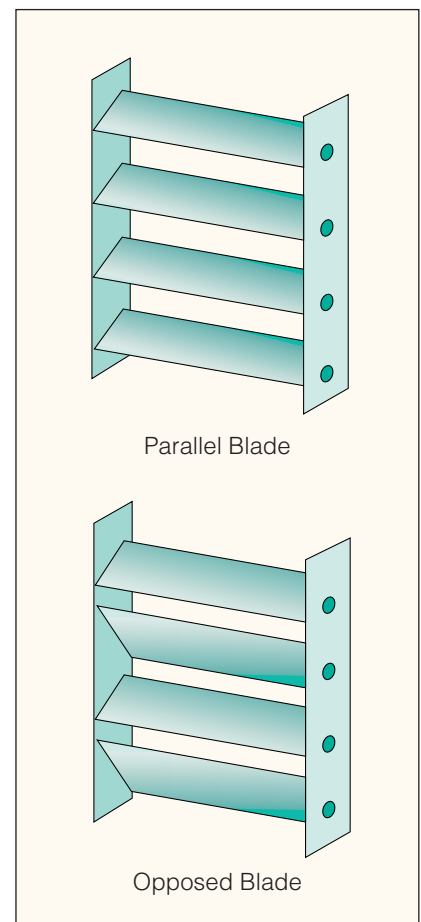


Figure 17 Dampers

## 9. VARIABLE FLOW CONTROL APPLICATIONS

This section covers:

- Variable Air Volume Air Conditioning Control.
- Air Quality Control.
- Heating/Cooling Demand Control.
- Cooling Towers/Dry Air Cooler Fan Control.
- Variable Flow Heating and Chilled Water Systems.
- Maximum Demand Control.
- Smoke Extract.

### 9.1 Variable Air Volume Air-Conditioning Systems

Variable Air Volume (VAV) air-conditioning systems have become widespread since the 1970s. They are most suitable where there is a cooling demand throughout the year, as in many modern office buildings.

The AHU supplies cooled air (normally 10 - 18°C, can be 6°C off ice storage) to VAV boxes which vary the volume with respect to space temperature. The AHU fans achieve variable volume by variable speed, variable pitch or inlet guide vane control.

VAV boxes with reheat and fan assisted boxes are available. Where the heating load is at the perimeter only, a separate heating system can be used instead of reheat coils. This is usually a compensated wet system, or can be a separate constant volume air system.

VAV design needs a multi-disciplinary approach due to the effects of one technology on another.

Benefits

- Often the most efficient form of air-conditioning.
- Highly flexible for initial/future fit-out requirements.
- Opportunity to reduce AHU size compared to multizone system if diversity allowed on cooling load.
- VAV systems, using DDC controls with communications, will generally require less maintenance in occupied areas than multizone systems with reheat coils.

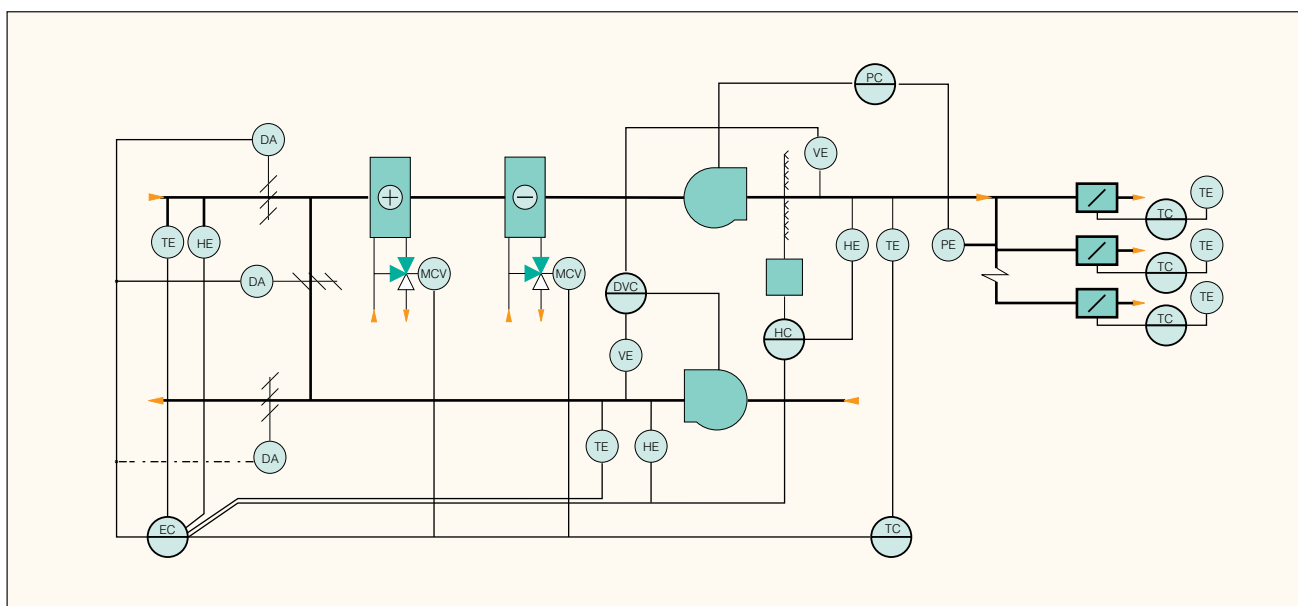


Figure 18 VAV air-conditioning system

#### Disadvantages

- Complex in comparison with other types of AC system.
- Integration of controls from concept stage essential.
- Special diffusers may be required for good room air distribution at low loads.
- Additional attenuation may be required for maximum velocity.
- VAV systems with conventional controls, or additional VAV box coils/fans, could require greater maintenance in occupied areas than multizone systems.

#### 9.1.1 VAV Control Types

- DDC controls recommended as they provide comprehensive setting of control parameters such as temperature setpoint, maximum/minimum volumes, etc. More accurate volume calculations. Also communications enable reset of supply condition, zonal time control, monitoring, etc.
- Pneumatic controls with instrument standard clean dry air supply suffer from a high degree of drift compared with electronic or DDC systems. No provision for reset of supply condition, monitoring etc.
- Self powered pneumatic VAV boxes controls not recommended due to drift, air supply filters blocking, control of pressure on system start up. Also no provision for reset of supply condition, monitoring etc.

#### 9.1.2 VAV Box Temperature Control

- Proportional space temperature control normally preferable for stability, ease of commissioning and economy of operation.
- Deadband required between heating and cooling where reheats.
- P&I control may be needed to reduce offset where reheats.
- P&I heating output only possible.
- Multistage P&I outputs must avoid overlap via common calculation point, etc.
- One temperature sensor per VAV box recommended.

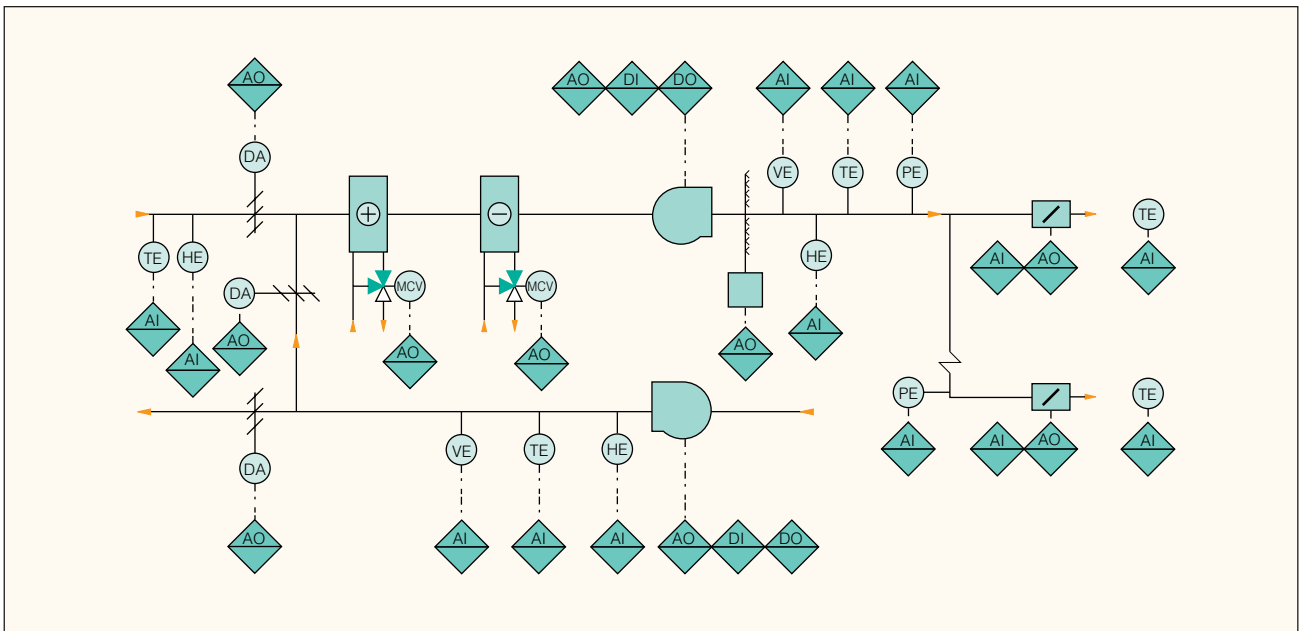


Figure 19 VAV system with DDC

- Sensor must be located in a representative position.
- One VAV box should not serve two different spaces.
- Several VAV boxes should not serve an area with only one temperature sensor.
- Averaging of sensors should only be used where VAV boxes may interact.

- Control with limited accuracy possible with ceiling mounted, return air or pendant sensors where sensor location difficult.
- Lack of suitable sensors locations often makes VAV totally inappropriate.

#### **9.1.3 VAV Box Volume Control**

- Most modern VAV systems use velocity reset (pressure independent) VAV boxes.
- System substantially self balancing.
- Good primary balancing should not be ignored.
- Pressure independent VAV boxes - primary air volume reset between minimum and maximum settings with respect to the space temperature.
- Velocity sensor must be matched to the individual model of VAV box.
- Velocity sensor linearised from maximum to minimum volume.
- Reheat normally at minimum volume to prevent energy wastage.

#### **9.1.4 Series Fan Assisted VAV Boxes**

- Continuously recirculate air.
- Allow better air distribution without 'dumping'.
- Additional cooling coils can be incorporated for high load areas.
- Higher capital cost.
- Additional maintenance.
- Additional energy consumption.

#### **9.1.5 Parallel Fan Assisted VAV Boxes**

- Cooling coil with additional fan.
- Fan enabled at high cooling loads.
- Additional noise at high loads.
- Higher capital cost.
- Additional maintenance.
- Only required for areas needing additional cooling.

#### **9.1.6 Static Pressure Supply Fan Control**

- Traditional method of control.
- P & I control mode required for stability and minimal offset.
- Static pressure sensed 2/3 the way down the supply duct.
- Pressure setting often higher than necessary to cater for uncertainties related to sensor location.
- Potential energy waste at low loads due to VAV boxes dissipating excess pressure.
- Potential noise problems at VAV boxes.
- Possible pressure control problems due to velocity lag.

#### **9.1.7 Static Pressure Reset Supply Fan Control**

- P & I control mode required for stability and minimal offset.
- Static pressure sensed before the first split or branch.
- Sensor not too close to the fan.
- 5 to 10 duct diameters recommended, more if possible with axial fans.
- Supply pressure reset with respect to summated cooling demand from VAV boxes.
- Allows for significant reduction in pressure at low loads.

- Low limit override from ends of system recommended.
- Communicating DDC controls required.
- Setpoint reset every 15 minutes or more to avoid potentially overloading communications.
- Potential energy savings and improved VAV box control at low loads.

#### **9.1.8 Demand Based Supply Fan Control**

- High volume of communications required.
- Settings are typical only.
- Fan initially run at nominal volume for five minutes.
- Enables VAV boxes positions to stabilise.
- If any box then has a damper position of greater than 90% open, fan volume gradually increased until all VAV box damper positions are below 80% open.
- If every VAV box damper closes to below 60% open and at least one VAV box damper is at, or below, the minimum of, say, 20% the fan volume is gradually reduced until at least one VAV box damper opens to 70%.
- This is in effect a form of floating control using the actual minimum and maximum requirements from individual VAV boxes.
- A pressure sensor near to the supply fan provides a maximum supply pressure limit and should be able to control the pressure at a fixed value in the event of communications failure.
- Potential energy savings and improved VAV box control at low loads.

#### **9.1.9 Fan Type**

- Variable pitch fans maintain minimum pressures at low volumes in an energy efficient manner that cannot be achieved with variable speed fans.
- Where static pressure control is less than ideal, the advantage of variable pitch at low loads is enhanced.

#### **9.1.10 Extract Fan Volume Control**

- Extract volume must be controlled relative to supply volume to prevent under or over pressurisation of the space and to give economic operation of the extract fan.
- Aim is to provide a constant difference in volume between supply and extract.
- Velocity is normally sensed.
- Where duct sizes differ velocity must be converted to volume, or differential velocity must be reset with respect to the supply velocity.
- DDC allows volume calculation and is much more accurate than analogue electronic controls.

#### **9.1.11 Velocity Sensing**

- Velocity sensors require straight lengths of duct to give reasonably laminar flow.
- Do not locate velocity sensors close to fans.
- Do not locate velocity sensors where moisture carryover may occur (downstream and close to cooling coils or humidifiers).
- Locate velocity sensors where maximum velocity occurs, not in the AHU.
- Often difficult, if not impossible, to locate velocity sensors effectively.
- Flow grids sense average velocity, but where there is turbulence sensing will still be inconsistent.
- Flow grids are expensive and take up space within the ductwork.

- Flow grids are not commonly used unless high accuracy is required.
- A single point hot wire anemometer can be used for small ducts.
- Sensing velocity at a single point can give considerable errors.
- An alternative velocity sensor is effectively a multi-hole pitot tube device with two or more tubes inserted the full width of the duct.
- One or more tube(s) sense static pressure and the other tube(s) sense static plus velocity pressure (ie total pressure).
- A square root extractor linearises the differential pressure signal.
- Manual calibration via a velocity traverse of the duct is required.
- The multi-hole pitot tube device appears to be the best compromise in terms of cost and performance at the present time, but is dependent upon accurate on site calibration which can be difficult.
- Another approach is sensing velocity with multiple hot wire devices arranged in a matrix with averaging and linearisation.
- Where the supply ducts split near the AHU it can be easier to sense the velocities in two or more places downstream, convert to volume flow and summate the flows. This is only practicable using DDC.

#### **9.1.12 Calibrated Volumetric Output From Fans**

- Centrifugal fans are now available with volumetric outputs derived from differential pressure sensing of a calibrated point on the inlet cone.
- These have high levels of accuracy and should overcome the problems normally found with differential volume control.

#### **9.1.13 Fixed Schedule Extract Fan Control**

- The volume achieved across the full range of fan speeds (or pitch angles) is measured using pitot traverse methods.
- The volumes for supply and extract fans are fed into the control program.
- The extract fan is then controlled relative to the supply fan using this calibration.
- This method can work well but requires considerable setting up.
- Any mechanical linkage hysteresis will affect control accuracy and stability.
- Dirty filters can affect calibration.
- System changes may result in the control system having to be recalibrated.

#### **9.1.14 Space Differential Pressure Sensing**

- Differential pressure control of occupied areas is not generally recommended for commercial applications due to sensor location problems, sensitivity, system lags, etc.
- It is used in industries where pressure differences have to be maintained between areas eg pharmaceutical areas.

#### **9.1.15 Filter Status**

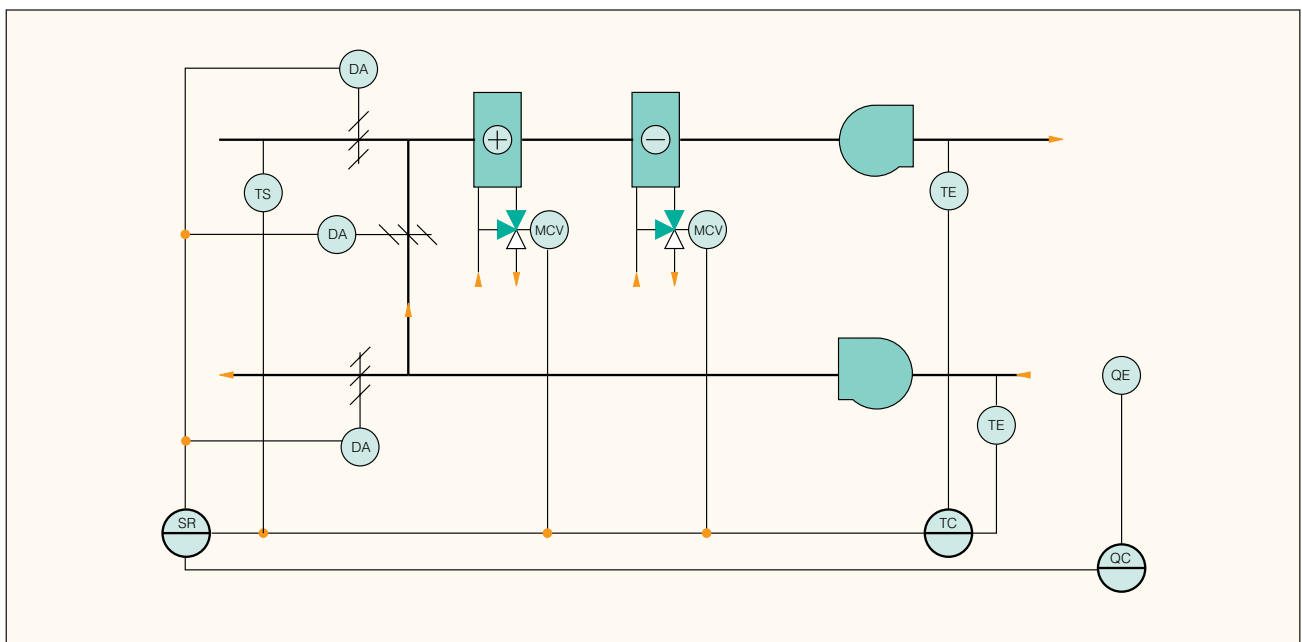
- VAV systems - air flow rate across the filter varies.
- Fixed differential pressure setpoint will not give the true status of the filter for filter blocked alarm.
- Advanced control systems setpoint can be reset in accordance with the air flow rate.
- Differential pressure sensor required instead of a differential pressure switch.

## 9.2 Air Quality Control

- Buildings with variable occupancy such as cinemas and theatres.
- Areas where pollutants can be a problem such as underground car parks.
- Air quality control can be used to control the minimum fresh air quantity in systems with recirculation, and the total volume of air in full fresh air systems.
- Alleviation of problems associated with sick building syndrome can require better control of fresh air volume than previously.
- Minimum fresh air setting normally caters for full occupancy.
- Minimum damper positions often arbitrary.
- Fresh air often oversupplied resulting in energy waste.
- Minimum fresh air quantity of a VAV system is difficult to set due to the varying volume of the main plant.
- With VAV systems it is normally cheaper to control minimum fresh air quantity by air quality than by other methods. The higher cost of air quality control can be recovered through reduced running costs.
- See 9.2.3 for CO<sub>2</sub> Air Quality Sensors, 9.2.4 for multiple contaminant Air Quality Sensors.

### 9.2.1 Recirculation Systems

- The supply extract and recirculation dampers are modulated to provide the minimum fresh air required as sensed by a space, or duct, air quality sensor.
- In the event of free cooling being required, the dampers are overridden to provide a greater quantity of fresh air.

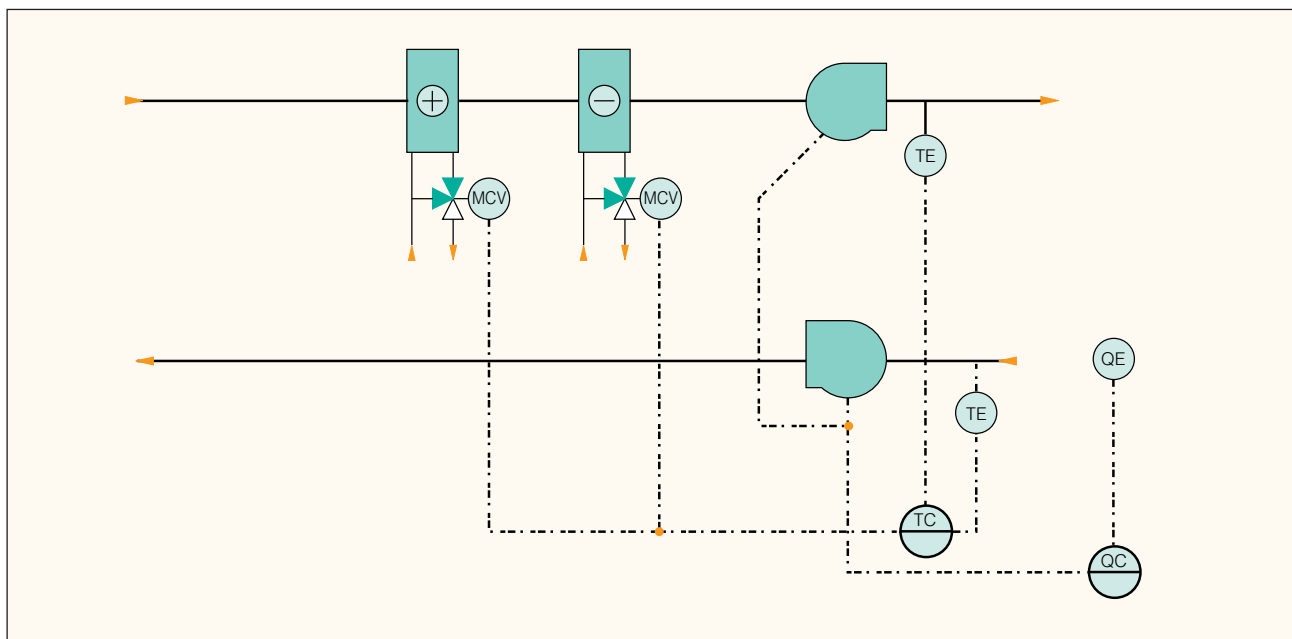


**Figure 20 Recirculation system air quality control**

### 9.2.2 Full Fresh Air Systems

- Full fresh air constant volume systems are used where recirculation of air is not desirable because of potential contamination such as in hospitals.
- Also used where recirculation not possible due to physical constraints of building.
- Heat recovery is available in the form of run around coils, heat wheels, etc.
- Air volume in hospitals is normally constant regardless of load up to 24 hours per day. This ensures that the correct relative pressures between critical rooms such as operating theatres and other areas are maintained at all times.

- Considerable economies in running costs can be made by converting a full fresh air system into a variable flow system with the air flow controlled with respect to air quality.
- These systems are not true VAV systems, which are far more complex and expensive.
- Flow turndown limited to ensure adequate air flow to provide sufficient heating and cooling to prevent stratification, cold air 'dumping', short cycling, etc.
- Even if turndown limited to 70% of the maximum flow, fan power would be less than half of that needed for full flow.
- In practice, many applications will be able to achieve far greater turndown in flow.
- Heating and cooling required will also be reduced.
- The heating and cooling controls should be in good order to obtain maximum benefits.
- Control valves in particular should be correctly sized to achieve the degree of turndown necessary for good control.
- Proportional balance of the system may need to be checked.
- The use of diffusers designed to provide better air distribution at low flow rates should be considered to increase the turndown in flow that is acceptable.
- Lower minimum air flow rates may be acceptable during unoccupied periods in operating theatres etc, as long as pressures are maintained.
- The minimum extract fan volume should be set in relation to the minimum supply fan volume. Normally set to give a constant difference in volume between the supply and extract.



**Figure 21 Full fresh air system air quality control**

- A fixed schedule method of extract fan control will normally be adequate due to restricted flow turndown.
- A local manual override for full air volume may be required for operating theatres or laboratories.
- A timing device may be used to reset the air flow rate back to the reduced rate after a period of time. This should not be so short as to cause the need for reset during an operation.
- Local reset to revert to automatic control and an indication lamp indicating manual override should be incorporated.

### 9.2.3 CO<sub>2</sub> (carbon dioxide) Air Quality Sensors

- The CO<sub>2</sub> sensor primarily measures carbon dioxide in parts per million (ppm).
- Control can therefore be easily achieved to maintain maximum CO<sub>2</sub> levels by varying fresh air content.
- The units are expensive and are normally only suitable for room rather than duct mounting, although sampling from a duct is possible.

### 9.2.4 Multiple Contaminant Air Quality Sensors

- The multiple contaminant sensor is a preheated semiconductor which reacts to a number of gases.
- Suppliers claim that it has been proven against the CO<sub>2</sub> sensor and meets the stringent Swiss fresh air laws.
- Room or duct mounting versions available.
- Far lower cost than a CO<sub>2</sub> sensor.
- No defined calibration.
- Set up by empirical values and repeated tests on site under differing occupancy conditions.
- Sensor may also be affected by oxidising and reducing gas contaminants.

## 9.3 Heating/Cooling Demand Control

- Heating/cooling demand control varies the ventilation rate in accordance with the heating or cooling demand.
- It may be used instead of, or as well as, air quality control.
- The air flow volume of a constant volume air-conditioning system is determined according to the maximum heating and cooling loads.
- Considerable energy can therefore be saved by reducing the air flow volume when there is reduced demand for heating or cooling.
- Considerable savings are possible in applications where the load varies according to occupancy such as cinemas, theatres, airport lounges, etc.
- Heating/cooling demand control of single, or multizone, air-conditioning systems schedules the air volume between minimum and maximum in accordance with the total heating or cooling load.
- This is not a true VAV system which provides variable flow to each zone according to load.
- The maximum volume required for heating may be different to that required for cooling.

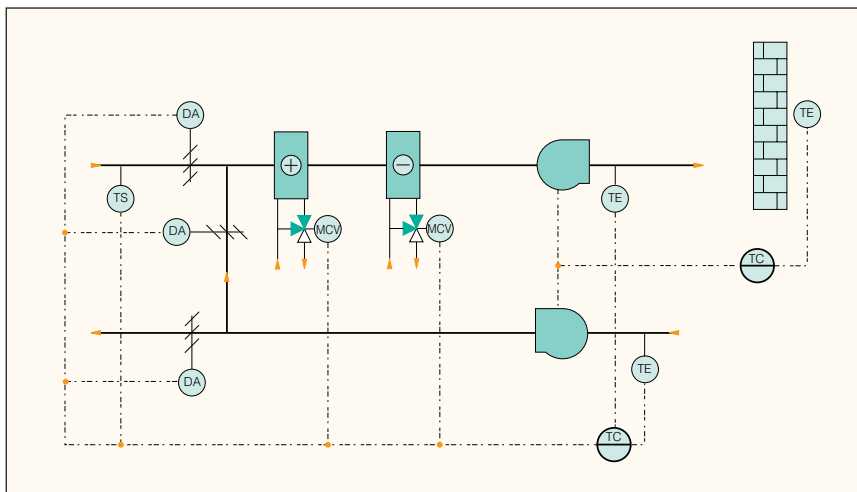


Figure 22 Outside temperature reset ventilation control

- The minimum volumes should be set in a similar manner to air quality control.
- Control of the extract fan should also be similar to air quality control.
- A simple alternative control strategy suitable for some applications can be to reset the flow rate with respect to outside air temperature.
- Where a building has a high glazed area, solar reset of the schedule may be necessary.
- An alternative to the use of variable flow fans can be the use of several packaged AHUs serving the same area.
- Care must be taken to ensure adequate air distribution at all times and an overall control system that controls all the AHUs in sequence is essential.
- Control must be more sophisticated than simply enabling each unit and letting it run under its own packaged control as, when load decreases, each unit will reduce its heating/cooling output and they will all stay running.
- Individual control can also lead to some units cooling and some heating the same space.
- Although the use of several packaged units may appear to be a lower cost solution, care should be taken to ensure that the full cost of an effective control system is included in the calculations.

#### **9.4 Cooling Tower Fan Control**

- Cooling towers are normally controlled by modulation of the water flow over the tower.
- Up to one-third of the cooling provided without the fan operating.
- After this point the fan is switched on and off to provide control of the water temperature.
- More sophisticated systems have two speed fan motors or inlet dampers on centrifugal fans which give better control and reduce energy consumption.
- Variable speed fans give much better control than two speed fans and are much more energy efficient than inlet dampers.
- Condenser water temperature is not critical and generally the lower the temperature the less energy used by the compressor.
- There will always be an optimum condenser water temperature for a given combination of condenser, compressor, refrigerant and evaporator, and the closer the condenser water can be controlled to this, the more efficient the plant will be.
- An induced draft cooling tower could have spray drift due to the wind in exceptional circumstances.
- If this is possible, positive air flow as soon as the water flows over the tower should be considered to minimise the possibility of Legionellae infection. Variable speed fans would give much better control in these circumstances.
- Variable speed fans can also result in quieter systems.
- Particular care must be taken with propeller fans to ensure that critical speeds which cause vibration and noise are avoided. In the typical location of a cooling tower on a roof this can be very disturbing to occupants.

#### **9.5 Dry Air Cooler Fan Control**

- Operation and control is similar to cooling towers.
- Minimal cooling effect without the fans operating.
- Two speed fans are often used.
- Multiple fans provide additional stages of operation and gives backup.

## 9.6 Variable Flow Heating and Chilled Water Systems

- Most chilled water and heating systems are constant volume.
- Constant volume systems use the same amount of energy for pumping throughout the year regardless of load on the system.
- Constant volume systems use three port valves which bypass the flow around the loads when not at full load.
- Variable flow systems use two port valves which close on reducing load and reduce the total flow of the system.

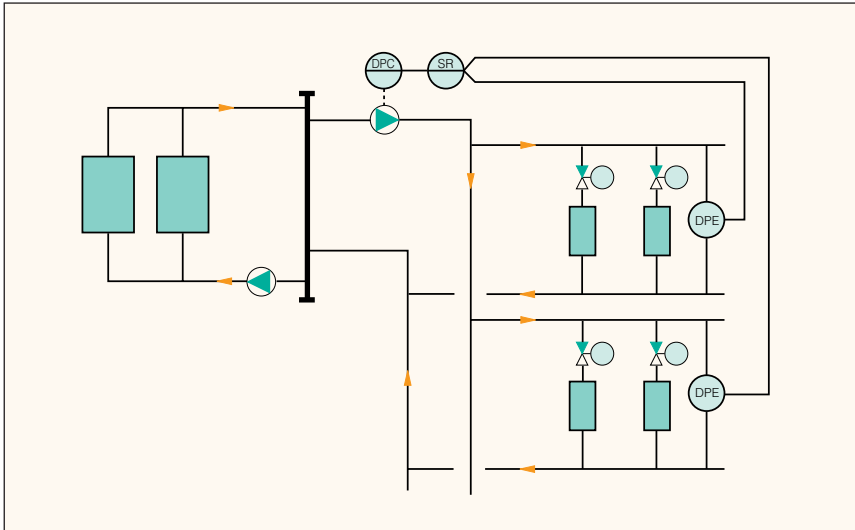


Figure 23 Variable flow heating or chilled water system

- Variable speed pumps respond to the reduced demand and decrease the flow of the pumps so that they match the load of the system.
- Two pipe systems have been normally used since the 1960s for all heating and chilled water applications.
- Single pipe systems were used for heating systems up until the 1960s. Local flow to the heat emitters (normally radiators) is by gravity circulation and when this is shut down the main heating flow is not affected.
- Variable flow can be applied to single pipe systems, however, it cannot be controlled with respect to differential pressure and the amount of flow turndown may need to be limited.
- Considerable energy savings can be achieved with the use of variable flow systems.
- Heating systems normally only require maximum flow during the boost period which is a small percentage of total heating time.
- Coil bypass pipework and regulating valves can be eliminated, thus reducing capital costs and commissioning.

### 9.6.1 Control Valves

- Two port control valves are used in variable flow systems instead of three port valves used in constant flow systems.
- Where an existing constant flow system is being converted to variable flow, the bypass of each load can be closed and the three port valve will work as a two port valve, although this is not ideal.
- Two port control valves with an equal percentage characteristic should be used for variable flow application.
- The equal percentage characteristic (also known as logarithmic or proportional uniform percentage) gives a constant percentage change in the rate of flow for each unit change in valve stroke.

- In practice this means that with an authority of 0.3 to 0.5, a near linear heat output to valve stroke is maintained.
- A three port valve normally uses a parabolic or quadratic characteristic to maintain a near constant overall flow rate when combined with a linear or complementary bypass port.
- To give a near linear heat output, with a parabolic or quadratic characteristic, the three port valve requires an authority of 0.5 to 0.8.
- Valve characteristics are based on a constant differential pressure being maintained across the valve and variable flow part of the circuit.
- Where the pump is controlled at a constant differential pressure, valves should be sized against the total system pressure loss to the valve.
- This is extremely complicated and the pump energy required to overcome valve pressure losses can negate all savings from the system being variable flow.
- The use of a variable speed centrifugal pump, controlled with respect to differential pressure at a point near the load(s), allows the effects of the distribution system pressure loss to be largely ignored in valve sizing.
- The control valve can therefore be sized relative to the load and associated pipework.
- An authority close to 0.5 should be used rather than 0.3 to minimise the effect of variable differential pressure.
- Systems must be designed with low distribution system pressure losses to ensure minimum variation in differential pressure and minimise pumping energy.
- Ideally an analysis of the system at various loads should be undertaken to ensure effective control.
- No individual coil should have a significantly higher pressure loss, as the whole system will need to be run at the higher differential pressure purely to satisfy the one item.
- Authority of the valve relative to the design differential pressure of the system at the loads (not the pump) rather than the individual coil may be considered.
- The turndown (or rangeability) of control valves used for variable flow application is particularly important.
- Valves with a turndown of at least 50 to 1 should be used.

### **9.6.2 TRVs**

- Thermostatic radiator valves (TRVs) are commonly used on heating systems to provide a cost effective form of space temperature control.
- TRVs are self-actuated and are primarily designed for use on radiators, although they can be used on some other forms of emitter such as natural convectors.
- There have been a number of problems with the application of TRVs such as heat transfer to the sensing element, sticking after summer shutdown, etc.
- Most of these problems have now been overcome with improved design, although TRVs do have limitations compared with motorised control valves.
- The use of variable speed pumps with TRVs provides significant benefits compared with constant speed pumps.
- The maximum differential pressure is limited enabling TRVs to control and close more effectively.
- Noise is also reduced at low loads.
- TRVs are modulating control valves, although effective turndown and control characteristics can be limited compared with other control valves.

- TRVs should be used on compensated circuits which provide primary control of heating output with respect to ambient temperature.
- Compensated circuits are required for most commercial buildings in accordance with the current Building Regulations.
- The TRV therefore provides a trimming function to match heat output to the requirements of the individual space.
- The pressure drop of a radiator is very low and TRVs are rarely sized to provide an authority relative to the radiator.
- The variation in pressure of a distribution system, even when well controlled, is likely to be far greater than the emitter pressure losses.
- A practical solution is to size the TRV to provide a nominal pressure drop of 5 kPa and ensure that the system differential pressure is below the maximum differential pressure of the TRV.
- With a typical pump differential pressure of 60 to 70 kPa reasonable control should result although turndowns of 50 to 1 cannot be expected.

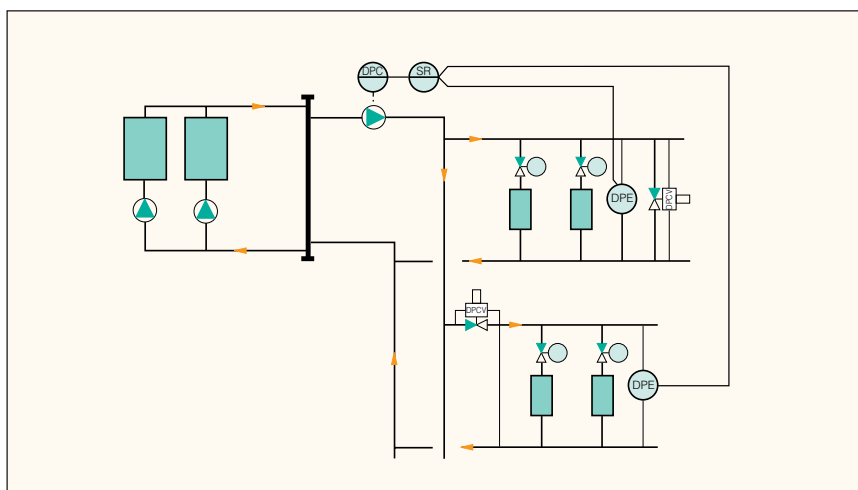
### **9.6.3 Differential Pressure Control**

- A distribution system normally serves several floors or zones.
- A differential pressure sensor should ideally be used for each leg.
- The pump should be controlled to maintain a constant differential pressure at the leg with the lowest differential pressure.
- Control should preferably be in a P&I mode to reduce offset from the setpoint with stability of operation.
- For small buildings, one differential pressure sensor at the end of the index circuit may be sufficient.
- Pumps with in-built VSDs and differential pressure control are now available. Where the system is small and has low distribution losses, constant pump differential pressure control may be adequate.
- Pumps with variable differential pressure control are also available. These reduce the differential pressure at the pump as speed reduces. This will effectively provide constant or reducing differential pressure at the loads and offer a very good control strategy at low cost.
- A similar strategy could be used for systems with separate VSDs. However, reset of differential pressure from output speed, when output speed is used for control of differential pressure, could easily result in an unstable control loop.
- The differential pressure setpoint could be reset with respect to circuit load, or summated demand where this is available as an output from the control system.
- Alternatively, the setpoint could be reset with respect to outside air temperature, reducing differential pressure with an increase in outside air temperature for heating systems and vice versa for cooling systems.
- A simple differential pressure reset function has considerable potential to assist stable control at low loads and reduces pumping energy.

### **9.6.4 Maximum Differential Pressure Control of System Legs**

- On sites where disparity is likely and separate circuits are not possible, such as large buildings with little space for services, maximum differential pressure control of system legs may be necessary to assist the controllability of lightly loaded legs.
- Ideally systems should be analysed for likely combinations of loads on branches, to determine where maximum differential pressure control is required.
- Maximum differential pressure bypass control valves can be used to bypass the flow in the event of high differential pressure.
- They are normally located at the end of the system leg for maximum differential pressure variation.

- Maximum differential pressure bypass control valves must not be set as constant differential pressure valves as excessive flow would result for much of the time.
- Low differential pressure settings must be avoided, as they can create a constant flow and negate the whole purpose of the variable flow system.
- Low differential pressure settings can also create interaction with the pump speed differential pressure control system.
- Settings should normally be at least 1.5 to 2 times the differential pressure at the point on the system necessary for full flow in the leg, to avoid interaction.
- Ideally settings should be determined by dynamic simulation.
- In-line pressure differential control valves can be used instead of differential pressure bypass control valves.
- In-line pressure differential control valves control the maximum differential pressure of the leg by regulating the pressure of the flow to the leg.
- They have the advantage that flow is not bypassed and energy is not wasted by recirculating water at low loads.
- The disadvantage is that the in-line location creates additional resistance and has some additional energy cost at all times, particularly at full load.



**Figure 24 Differential pressure control valve locations**

- In-line differential pressure control valves may be set to maintain a constant differential pressure sufficient for full flow in the system leg.
- Control valve sizing can therefore utilise an authority close to 0.3 and reduce overall pressure loss whilst maintaining good control characteristics.
- This can minimise the energy penalty of additional resistance from the in-line pressure differential control valve.
- Care must be taken with the use and selection of in-line differential pressure control valves. Most of the guidance from suppliers assumes that the pump is to be controlled at a constant differential pressure, and that the differential pressure across the loads will vary by an amount many times greater than the pressure drop across the load to be controlled.
- Systems must be designed for moderate to low distribution pressure losses and controlled to provide as near possible constant differential pressure at the loads.
- In-line differential pressure control valves should therefore be sized to provide an appropriate authority, relative to the variation in differential pressure, on the part of the circuit to which they are to be applied.
- Where self acting differential pressure control valves are used an adequate proportional band must be ensured to avoid unstable operation.

- Motorised differential pressure control valves can be controlled via local controllers or more advanced control systems. P&I control modes may be used to eliminate offset and provide more accurate control.

#### **9.6.5 Automatic Flow Control Valves**

- Automatic flow control valves should not normally be used in variable flow systems as they try to maintain a constant flow, which is the opposite of what is required for energy efficiency.
- Automatic flow control valves can be set up as maximum flow limiting valves. However, this should not be required with variable flow systems controlled with respect to system differential pressure.

#### **9.6.6 Zoning of Circuits**

- Where there is likely to be a large disparity in loads between one zone and another, for instance the north and south facias of a building, separately pumped circuits should be considered.
- Separate zone circuits can add considerably to the controllability of systems and consequently to the economy of operation.
- Capital costs may be increased.

#### **9.7 Circuit Interaction**

- Boiler and chiller manufacturers normally require a constant flow through their products to ensure safe operation.
- With careful control variable flow might be possible, the complication, cost, warranty problems and potential safety problems normally prohibit variable flow through boilers and chillers.
- To ensure constant flow through the heating or cooling source, and variable flow to the loads, separate primary and secondary circuits must be created.
- A common header or buffer vessel must be used to 'decouple' the primary and secondary circuits and prevent circuit interaction.
- Separate flow and return headers do not have the same effect and must not be used.

#### **9.8 Pump Configuration**

- Most constant flow systems have run and stand-by pumps, each rated at the full system duty.
- Considerable capital cost savings can be made with variable flow systems by installing two duty pumps in parallel.
- The pumps are normally controlled together at the same speed with respect to the duty required.
- In the event of failure of one pump, the other would automatically increase speed to that required, up to its maximum speed, due to the control being a closed loop.
- At the maximum speed of one pump, just over 70% of full flow will be available if the pair of pumps are exactly matched to the system maximum flow requirements. This is due to pressure loss rising as the square of the flow rate.
- In the common event of over-capacity of the pumps then a greater flow will be available with one pump operating.
- Most heating and cooling systems operate at considerably less than 70% capacity during the majority of their operating season and even in the event of one pump failing during peak load conditions the consequences will not normally be that great.
- Capital cost is saved not just on pumps but also on the variable speed drives, cabling, isolators etc.
- It must be made clear to control panel suppliers, electrical distribution system designers etc. that the motors are both duty and not a duty/stand-by arrangement which is normally used.

- For systems where 100% capacity is essential, two shared duty pumps and an equal size stand-by pump may be more economical than two 100% capacity run and stand-by pumps.
- For large systems with a high turndown in load, such as district heating systems, a number of pumps may be used.
- Combinations of fixed speed and variable speed pumps may be used together, although with the reducing relative cost of variable speed drives this is not as economically beneficial as it has been in the past.

### 9.9 Single Pipe Systems

- Single pipe systems do not reduce the system flow when the radiator flows are automatically (via TRVs) or manually regulated.
- Control of system flow can be achieved by controlling the flow with respect to ambient temperature or system differential temperature.
- Control with respect to ambient temperature is an open loop control, and care must be taken to ensure that adequate flow is maintained at all times for anticipated loads.
- The minimum flow rate should also be limited via the minimum speed on the variable speed drive.

### 9.10 Maximum Demand Control

- Maximum demand control is used to keep the maximum electrical demand as low as possible, and therefore avoid cost penalties.
- Switching items off at periods of peak load (load shedding) is often not popular, or not practical, and therefore restricts the uptake of maximum demand control.
- The use of maximum demand control to restrict the flow of fans and pumps rather than turning items off will enable greater use of maximum demand control.
- Maximum demand tariff settings can be reduced without significant reduction in services.
- Significant cost savings can result.
- The controller/BMS predicts that the tariff limit will be exceeded from the rate of increase in consumption.
- The maximum demand period should be synchronised with the tariff meter.
- Normally via volt free contacts momentarily operating at the beginning of each timed period of maximum demand registration.
- Systems that purely use instantaneous consumption will be less accurate.
- Care must be taken that turning items off or reducing flows does not cause damage to other equipment.
- For instance cooling tower flows should not be restricted if the chillers are allowed to operate at full load.
- Demand can be restricted in unison or according to priorities.
- For most buildings a strategy can be devised which will have minimal effect on availability of services but can provide effective savings on the supply tariff.
- The use of maximum demand control with variable flow will be most cost effective where it is used in association with regulation via variable speed drives, or demand based variable flow methods.

### 9.11 Smoke Extract

- Supply and extract systems for applications such as shopping malls need to maintain the desired air change rate but also be capable of high extraction rates in the case of fire.
- This can be undertaken economically by applying variable speed drives to fans sized for smoke extract and operating them at low speeds for normal usage.

## 10. VARIABLE FLOW CONTROL SELECTION PROCEDURES

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### 10.1 Fan Type

- The selection of a fan type is primarily determined by the application.
- Where a choice is available the most efficient fan type should normally be chosen.
- For instance a cooling tower can have a propeller fan for induced draft, or centrifugal fan for forced draft.
- The centrifugal fan is more efficient, controllable and quieter and should be selected.
- All fans using speed control for variable flow reduce static pressure according to the square law.
- This coincides with the reduction in pressure loss in a fixed configuration of ductwork.
- Where ductwork is not of fixed configuration, or for VAV systems a minimum pressure has to be maintained at terminal boxes regardless of flow.
- A centrifugal or mixed flow fan will only maintain the pressure by operating at a higher point on its characteristic curve. Operation at this point is less efficient.
- In these circumstances a variable pitch axial fan can maintain the required static pressure in a more energy efficient and stable manner.
- Inlet guide vanes, disc throttles and dampers are not generally recommended for energy efficient operation.
- Disc throttle is acceptable for systems with restricted turndown.

### 10.2 Pump Type

- The workshop only considers the application of variable flow control to centrifugal pumps.

### 10.3 Fan and Pump Selection

- The most efficient fan, or pump, for the application should be selected.
- Fan efficiency varies far more than pump efficiency due to range of fans available.
- Fans and pumps should be sized as accurately as possible to work at maximum flow near their point of most efficient operation.
- The use of oversized fans and pumps with efficient VSDs, or variable pitch, is far more economic than mechanical system regulation.

### 10.4 Shared Duty

- A pair of duty pumps, or fans, can be used rather than run and standby.
- Most applicable to pumps where run and standby normal.
- Fans normally only have standby motors.
- In the event of failure of one pump, or fan, the other will provide around 70% of the flow.
- Adequate for most circumstances until the other pump, or fan, is repaired.
- Closed loop control is necessary to ensure that the working pump, or fan, increases speed to provide required flow (up to maximum available) in the event of failure.
- Differential velocity control of the extract fans is necessary to provide closed loop control of the extract fans with VAV systems.
- Alternatively, an increase in speed of the operating fan could be programmed in the event of one fan failing, although this is more difficult to achieve satisfactorily.
- Non return valves and backdraught dampers must be used - additional system resistance.
- Capital cost savings include motors, drives, cabling and control panel size.

Fan	Application	Control Method		Energy Efficiency of Flow Control	Comments
Centrifugal	AHUs Forced draft cooling towers High pressure/flow ratio applications		PWM inverter	Good at all speeds	Most often used
		VSD	SRD	Marginally the best required	Special motor
			ECC	Less good at low speeds	Robust, no harmonics
		MSM		Good at fixed speeds	Limited application
		IGVs		Poor at lower volumes	Not recommended
		Disc throttle		OK down to 50%	Only recommended for limited flow turndown
		Dampers		Poor	Not recommended
Mixed flow	Large AHUs, VAV Medium pressure/flow ratio applications	Generally as centrifugal		As centrifugal	As centrifugal (No disc throttle)
Axial	Large AHUs, VAV Forced draft cooling towers Low pressure/flow ratio applications Smoke extract	Variable pitch		Good at all speeds	Electro-pneumatic actuation requires caution. Allows constant pressure variable flow
		VSD		As centrifugal	Good potential
		MSM		Good at fixed speeds	Limited application
		IGVs		Very poor	Not recommended
		Dampers		Poor	Not recommended
Propeller*	Non ducted applications, Condensers, Induced draft cooling towers	MSM		Good at fixed speeds	Most often used
		PWM inverter		Good at all speeds	Good potential
Cross and tangential flow*	Terminal units	MSM		Good at fixed speeds	Most often used
		PWM inverter		Good at all speeds	Good potential, also multiple motors
*Poor overall fan efficiency					

Table 2 Efficiency of fan control methods

Pump	Application	Control Method	Energy Efficiency of Flow Control	Comments
Centrifugal	All apart from positive displacement	PWM inverter	Good at all speeds	Most often used
		SRD	Marginally the best	Special motor required
		ECC	Less good at low speeds	Robust, no harmonics
		MSM	Good at fixed speeds	Common on small pumps
		In-built VSD - Inverter or variable voltage on small drives	Good at all speeds - variable voltage - less efficient than inverter	Now becoming very popular. In-built DP control available - pressure reset recommended

Table 3 Efficiency of pump control methods

### 10.5 Capital Cost

- The capital cost of the various methods should be compared with the energy savings offered.
- The relative cost of the methods varies dependent upon whether the application is retrofit or new.
- With retrofit installations the expected working life of existing motors and pumps should be considered.
- It is difficult to give guidelines on comparative costs as they can alter within a matter of months and also vary depending upon the equipment rating.

The following table provides an approximate indication, based on prices in late 1994.

Fan Variable Flow Control Type	Capital Cost Indication
Inlet guide vanes and disc throttle	Low cost
Dampers	Low cost for new installations, possibly high cost for retrofit
MSM	Low cost for new installations, high cost for retrofit
ECC	Lower cost than inverters or SRD for new installations for most motor sizes above 7.5 kW. Usually higher than inverters for retrofit
Frequency inverters	Highest cost apart from SRD for new installations, normally lowest cost for retrofit
SRD	Highest cost for new and retrofit
Pump Variable Flow Control Type	Capital Cost Indication
MSM	Low cost for new installations, high cost for retrofit unless pump is being replaced
ECC	Lower cost than inverters or SRD for new installations for most motor sizes above 7.5 kW. Usually higher than inverters for retrofit
Frequency inverters	Highest cost apart from SRD for new installations, normally lowest cost for retrofit
	Low cost when in-built into pump
SRD	Highest cost for new and retrofit
In-built VSD	Low cost for new and retrofit as package with pump

Table 4 Capital costs

- CE marked VSDs should now be used.
- Some very low cost frequency inverters have been available which may not be suitable for the application and cause excessive harmonics and RFI.
- Comparative costs are based on reputable manufacturers equipment.
- Most drives sold for building services applications are relatively low cost due to the lower starting torques required.
- Higher cost units, suitable for higher starting torques, if applied inappropriately in a building services situation, will lead to energy wastage.
- Star-delta starting of three phase motors necessitates six wire connections. If an inverter is used, three wire connections are required and savings on cabling costs can be substantial.

### **10.6 Fan Space**

- The size and shape of a plantroom can affect the fan selection.
- The ratio between length and width of fans varies between types, sizes and manufacturers of fans.
- Generally axial fans offer a more compact installation.
- Variable pitch axial fans are normally longer and outlet expanders to improve efficiency may add to the overall length.
- Inlet and outlet orientations can also affect the fan selection.
- Axial and mixed flow fans have substantially straight through flows.
- Centrifugal fan flows are at right angles.
- Minimum distances on the fan inlet can have a significant influence on efficiency and noise.
- Where the velocity is being sensed, it is essential that sufficient straight lengths of ductwork are allowed for accurate flow measurement.
- The amount of space required for flow measurement will normally be far in excess of any differences in size between fans.
- Where straight runs of ductwork are available external to the plantroom, velocity sensing can be located external to the plantroom, prior to any takeoffs.

### **10.7 VSD Space**

- Additional space is required in plantrooms for inverters and ECCs.
- Inverters can be mounted local to the fan or pump served, this reduces RFI from the motor cables.
- Inverters mounted in control panels should preferably occupy separate cubicles.
- This can considerably increase the size of the panels, although smaller size inverters are becoming available for small to medium motors.
- ECCs require additional space between the motor and fan.
- Alternative mountings are available to save space but these require the use of belt drives which reduce overall efficiency.
- The use of two duty pumps, or fans, may be considered for space reasons.
- This will not only utilise smaller motors but, where applicable, smaller inverter drives, control panels and even reduced space for wiring.
- Pumps with in-built VSDs are very space efficient.

### **10.8 Drive Type**

- The method of drive affects the overall efficiency.
- V - belt drives typically consume approximately 10% of the motor power.
- Toothed belt drives are more efficient - typically consume approximately 6% of the motor power.

- Use of belt drives in air-conditioning applications can move the motor out of the airstream and therefore reduce the cooling load.
- Direct drive pumps with variable speed control or multiple speed motors provide a more compact motor pump assembly than belt drive pumps.

### **10.9 EMC and Harmonics**

- EMC and harmonics with inverters and SRDs should not be a deciding factor for most applications.
- Potential problems should be minimised with EC certified devices.
- Where site particularly sensitive, or high proportion of total load, then variable pitch fans or ECC may be more appropriate.

### **10.10 Resonance and Pulsation**

- Resonances can be caused by fans at critical speeds.
- Normally only a problem with propeller fans although it can affect other types of fan.
- VSDs should have avoidable speed settings to bypass the critical speeds.
- Resonances are not normally a problem with pumps.
- A minimum speed setting may be necessary to avoid flow pulsation at low speeds with pumps.

### **10.11 Noise**

- Acoustic noise is produced by some types of VSD and can be a problem in certain applications.
- Noise levels are generally lower with modern devices.
- Generally variable flow should result in lower overall noise levels.
- Cooling towers, dry air coolers and air cooled condensers are far less likely to cause disturbance where fitted with VSDs than with fixed speed fans.

### **10.12 Installation**

- For a new installation the method of variable flow control should be determined at a very early stage in the design process as it affects many aspects of the installation.
- This is particularly true when choosing between variable pitch axial fans and variable speed centrifugal or mixed flow fans.
- Variable pitch fans with pneumatic actuation require a compressed air supply.
- Most installation problems with inverter drives have now been overcome with improved drives and methods of installation.
- There should be little problem provided the recommended methods are used.
- Facilities to bypass the drive in the event of failure may be important, although the cost and complication are normally not justified.

### **10.13 Maintenance**

- Inverters, SRDs, MSMs and ECCs require minimal maintenance.
- Much more maintenance is required with variable pitch fans, particularly where pneumatic actuation is used. Down times may be extended.
- Inlet guide vanes, disc throttles and dampers require regular maintenance.
- Where linkages are required between items, or items need to work in sequence, maintenance to ensure correct operation can be time consuming and is often poorly carried out.

#### **10.14 Selection Based on Cost Benefit Analysis**

- Where there is more than one practical option, an analysis of the costs and benefits associated with each option will indicate which method is more financially viable.
- Even if the decision as to the type of variable flow control has already been determined by other factors, it is normally necessary to undertake analysis to justify the capital investment.
- Such an analysis can vary greatly in complexity and the level at which it is pitched will depend on the amount of capital involved and company policy.
- This section details the most common methods of analysis which should be sufficient for most variable flow control installations.

##### **10.14.1 Costs and Benefits**

The total cost of the variable flow control installation should be calculated. This will include the following, where appropriate:

- capital costs
- operating costs
- maintenance costs
- design and specification costs
- installation costs
- project management costs
- disruption costs
- training costs
- commissioning costs
- additional energy costs if the system goes off-line.

Also, the total annual benefit or savings needs to be evaluated. Factors included in this are:

- energy cost savings
- operating cost savings
- maintenance cost savings
- savings from increased production rates or improved product quality.

Additional benefits such as improved environmental conditions are not normally quantified unless they have a direct effect on something tangible such as rate of production.

##### **10.14.2 Sensitivity**

- With all analysis methods changes in the basic parameters can substantially alter the end result.
- This applies particularly to investments which have a simple payback of three years or more.
- In these cases, the variables should be scrutinised for ranges of accuracy and calculations undertaken over the full range of the variables.

##### **10.14.3 Analysis Methods**

Having calculated the total costs and benefits, the following analysis methods can be used.

- Simple Payback
- Accounting Rate of Return (ARR)
- Discounted Cash Flow (DCF)

##### **10.14.4 Simple Payback**

- Organisations usually have stated payback criteria for new projects normally ranging from two to five years.
- Calculation of simple payback is the first step towards deciding whether a variable flow control installation is likely to be cost-effective.

- The simple payback is calculated by dividing the total project costs by the total annual benefits, as shown below.

Total Annual Benefit	£9 400
Total Project Costs	£16 300
Simple Payback Period	1.7 years

- The main disadvantage of the simple payback calculations is that it does not take into account cash flows beyond the payback period.
- Also, it does not enable decisions to be taken when comparing cases for which payback period is identical but costs and benefits are different.

#### 10.14.5 Accounting Rate of Return

- Accounting Rate of Return incorporates depreciation of equipment into the calculation.
- ARR is defined as the annual net benefit after depreciation divided by the total project costs.
- Depreciation charges are set depending on the nature of the equipment.
- The following example shows a calculation of ARR.

Total Project Cost £16 300

	Total Benefits £	Depreciation Charge £	Net Benefit £
Year 1	9400	2000	7 400
Year 2	9400	1600	7 800
Year 3	9400	1280	8 120
Year 4	9400	1024	8 376
Year 5	9400	819	8 583
Year 6	9400	655	8 745
		TOTAL	49 024

Table 5 Calculation of ARR

- ANNUAL AVERAGE = £8171
- $ARR = £8171 / £16\,300 = 50\%$
- The ARR, like simple payback, is only a rough indicator of the economics of the investment.

#### 10.14.6 Discounted Cash Flow (DCF)

- Neither simple payback nor ARR methods allow for the time in which savings are obtained.
- A scheme which generates higher savings in the early years facilitates further investment.
- DCF methods try to weight the value of savings to reflect this point.
- They incorporate interest rates into the calculations.
- At an interest rate of 7%, £100 invested would be worth £107 at the end of the first year and £114.49 at the end of the second year.
- Hence £114.49 in two years time would have a present value of £100.
- In general terms, the present value of a sum of money S saved in year 12 will be:

$$\text{Present Value (PV)} = S / (1 + I/100)^{12} \text{ where } I \text{ is the interest rate}$$

- If a variable flow control investment is considered which generates savings over a number of years, then for each year there will be a factor which relates the savings at year 12 to the present value.

- This is called the discount factor, and is defined below.

$$\text{Discount Factor} = 1/(1 + I/100)^{12}$$

- The effect of the discount factor is to reduce the value of savings achieved in the later years of a project life. Year 0 is defined as the present time and will always have a discount factor of 1.0.
- The Net Present Value (NPV) method is a DCF method.
- NPV involves calculating the present value of all yearly capital costs and net savings throughout the life of the project.
- The costs are defined as negative amounts, the savings as positive amounts.
- The total of all the costs and savings is the Net Present Value (NPV) of the project.
- If the value is negative, the project would be rejected, if positive it would be considered.

Calculation of the NPV is shown as follows:

An interest rate (or discount rate) of 12% has been used in the discount factor.

Year	Discount Factor (A)	Net Benefit (£) (B)	PV (£) (A x B)
0	1.0	-16 300	-16 300
1	0.893	7 400	6 608
2	0.797	7 800	6 217
3	0.712	8 120	5 781
4	0.636	8 376	5 327
5	0.567	8 583	4 867
6	0.507	8 745	4 433
		TOTAL = NPV = £16 933	

Table 6 Calculation of NPV

- Comparison of the NPVs over the projected lifetime will indicate which is the more viable investment.
- Projected lifetime will normally be longer than 6 years.
- Selection of an appropriate discount rate (interest rate) is critical to calculation of NPV.
- The rate will vary according to general and energy cost inflation as well as other variables.
- As a measure of the sensitivity of the investment to changes in the discount rate, the internal rate of return is frequently calculated.
- The internal rate of return is defined as the discount rate which makes the NPV equal to zero and can be imagined as the yearly net return on capital invested.
- It can be evaluated by working the NPV out for various discount rates and plotting the results graphically.

For the example above:

- A discount rate of 20% gives an NPV of £10 395.
- A rate of 30% gives an NPV of £4755.
- A rate of 40%, an NPV of £855.
- A rate of approximately 42% will give an NPV of zero - this is the internal rate of return.

Spreadsheets can also be used to automate these calculations. Most companies have their own guidelines as to a minimum acceptable value of internal rate of return.

## 11. ENGINEERING AND INSTALLATIONS

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### 11.1 Introduction

- Standards that have been developed to ensure reliable operation are included.
- These should be regarded as minimum standards.
- Manufacturers and specialist supplier standards should be used - particularly for CE certified devices.
- Care should be taken where lower cost methods of installation are promoted.
- Lower cost methods available at the present time have been investigated and will not provide the necessary standards for long term reliable operation.

### 11.2 Integration into Systems

- For a variable flow application to be successful, both the means of providing variable flow and the method of control must be integrated into the system being controlled.
- For VAV systems this should be part of the fundamental design of the system.
- A VAV system must have suitable locations for room and duct sensors.
- If suitable locations are not available, the system will not work properly and may be uncontrollable.
- In this situation other forms of air-conditioning may be more suitable.
- For retrofit applications, the operation of the existing system must not be compromised.
- This necessitates undertaking a survey of the existing installation.
- The following actions should be included within the survey.
  - Establish existing loads.
  - Identify existing problems with design, operation and maintenance.
  - Establish the need to derate power factor correction capacitors due to increased levels of harmonics leading to overheating; advice should be sought from the capacitor manufacturers.
  - Checking whether the circuit contains residual current control devices (RCCDs). RCCDs are not normally suitable for use with rectified loads.
  - Use of RCCDs on circuits into which inverters are likely to be fitted, is uncommon in the UK.
  - Checking the age and construction of motors.
  - Many older motors will overheat if an inverter drive is applied to them.
  - Specialist advice should be sought if this is felt to be a potential problem.
- Costs involved with rectifying existing problems, or replacing equipment that has reached the end of its useful working life, should be separately identified.
- Prevention of interaction between constant and variable flow circuits must not be overlooked.
- Whilst it may increase the payback period, additional work to ensure long term successful operation must not be ignored.

### 11.3 Electromagnetic Compatibility

- The EMC requirements of equipment is at the present time subject to national legislation.
- EC legislation with respect to EMC is in a transitory phase at the present time.
- From 1 January 1996 all equipment sold in the UK will have to conform to EC standards and be certified.

- Basically devices may not emit, or be susceptible to, certain levels of EMC.
- The European Committee for Electrotechnical Standardisation, CENLEC, has drawn up standards (ENs) based on respective IEC standards.
- The following generic harmonised European EMC standards have been issued:
  - BS EN50081 EMC generic emissions
  - BS EN50082 EMC generic immunity
- There will also be product family standards.
- These have yet to be defined for frequency inverters.
- Existing installations may have to be brought up to the proposed standards.
- The requirements of the above standards are dependent upon the operating environment.
- These are 'industrial' and 'residential, commercial and light industrial'.
- These are currently categorised according to the supply being via individual or shared distribution transformers.
- This categorisation may be revised for the product family standards.
- The generic harmonised European EMC standards require CE certified products.
- The product certification requires that it is installed in accordance with the manufacturer's instructions to ensure compliance.
- The following may be typical of compliance requirements:
  - Incorporation of a matching supply filter.
  - Use of SWA motor cable with a high RFI screening factor.
  - Limiting inverter switching frequencies to reduce RFI.
- It should be noted that on installations with a high proportion of filtered devices the filters could interact, with undesirable consequences.
- Calculations may be required to ensure that interaction does not occur.

#### **11.4 Harmonics**

- Harmonics are created by both frequency inverters and SRDs.
- ECCs and MSMs do not cause harmonics.
- Harmonics are sine wave currents reflected on to a power supply at frequencies that are a multiplication of the frequency of the supply.
- Harmonics are caused by the rectification of alternating current (AC) to direct current (DC).
- Harmonics produce a voltage drop at the harmonic frequency and therefore a voltage distortion.
- This will affect other loads supplied from the same point and can also flow into the supply system.
- Power factor correction capacitors can also be affected by harmonics causing premature failure due to overheating.
- Frequency inverters reflect harmonics on to the distribution system due to the inherent nature of rectification from AC to DC.
- The effect of these must be carefully considered and the greater the percentage of total load controlled by inverters the greater the potential problems.
- An uncontrolled rectifier with a six pulse bridge, which is used in a typical PWM inverter, will produce harmonic currents at the 3rd, 5th, 7th, 11th and 13th harmonic of the supply frequency.
- The magnitude of the harmonic in a perfect circuit is in inverse proportion to the frequency.

- In practice, the 5th harmonic normally is the largest and would typically be about 28% of the line current where DC link filtering is used.
- Harmonics above the 13th are normally negligible and are not usually considered, although occasionally devices will produce greater harmonics at higher frequencies.
- Most modern CE certified inverters will have filters to reduce the harmonic content reflected back into the main supply.
- For most applications the installation of VSDs can be engineered so that harmonics are within acceptable limits at little additional cost.
- Where there is a high proportion of the load being controlled by VSDs, or the site is particularly sensitive, additional measures can be taken to reduce harmonic effects.
- A frequency inverter rectifies AC to DC and then reproduces the AC cycle at a different frequency.
- The waveform is not a perfect sinewave and will therefore also produce harmonics on the outgoing supply to the motor.
- This can cause overheating of the motor windings and necessitate derating the motors.
- These harmonics have been significantly reduced by the use of modern technology such as IGBTs.
- These provide high speed switching of the output voltage and create a waveform that is much nearer to a sine wave.
- The harmonics on modern inverter outputs are now normally insignificant and motor derating is not required.

#### **11.4.1 Standards**

- Harmonics reflected into the power supply of a building can cause problems with electronic equipment within and external to the building.
- Regulations therefore exist to prevent reflected harmonics causing problems on the supply system.
- Harmonics reflected on to the supply system are governed by the Electricity Supply Council recommendations G5/3 - Limits for Harmonics in the United Kingdom Electricity Supply System.
- These are supplemented by the British Electricity Boards ACE Report No. 73 which gives further definitions and guidelines.
- The magnitude of the harmonics at the point of common coupling to the supply system can be determined and must be submitted to the electrical supply authority for approval.
- Approval may depend upon the nature of the supply in the area.
- In an area that has a high industrial load the supply may be relatively 'dirty' and stricter limits may be applied than in other areas.
- The harmonics induced on to the supply at the point of common coupling are dependent upon a number of factors.
- G5/3 gives three stages of acceptance.
- Stage 1 concerns individual items of equipment and would often be exceeded where the point of common coupling is 415 V with a typical 6 pulse 3 phase converter being limited to 12 kVA.
- For installations with a 6.6 or 11 kV supply at the point of common coupling the limit for 6 pulse 3 phase converter is 130 kVA.
- Where Stage 1 is exceeded the installation may be accepted subject to certain requirements in Stage 2.
- Principally the total harmonics currents falling below those listed in table 2 of G5/3.

- Details of the harmonics produced by all connected devices have to be added together in accordance with G5/3 procedures for this calculation.
- A guide to acceptable sizes is included in G5/3 appendix table 1.
- This shows the maximum of 150 kVA for a 6 pulse uncontrolled rectifier with a 415 V point of common coupling and 1000 kVA for a 6 pulse uncontrolled rectifier with a 6.6 or 11 kV point of common coupling.
- These figures are for single devices; the maximum load for multiple inverters is greater according to coincidence factors shown in table A3.
- Measurement of existing levels of harmonics at the site may be required.
- Where Stage 2 levels are exceeded the installation may still be accepted under Stage 3 levels.
- This involves calculation of the harmonic voltage distortion limits at any point on the system, with a total harmonic distortion below 5% for 415 V and 4% at 11 kV.
- This is far more complex to work out and again may involve measurement of the existing levels of harmonics at the site.
- In practice for buildings with a 415 V supply at the point of common coupling, the use of frequency inverters may require detailed calculations to be submitted to the supply authority.
- For buildings with a 6.6 or 11 kV supply there is unlikely to be a problem with the supply authority.
- However, it would be wise to ensure that harmonic levels are kept as low as possible within the building and preferably to levels for a 415 V supply.
- Twelve pulse rectifiers can be used instead of 6 pulse as these only produce harmonics at the 11th and 13th, which are of a small magnitude.
- Twelve pulse rectifiers are expensive as a phase shift transformer has to be included at each rectifier.
- The G5/3 Stage 2 guidance for 12 pulse uncontrolled rectifiers gives 300 kVA for 415 V and 3000 kVA for 6.6 or 11 kV.
- A lower cost method of achieving the same effect as 12 pulse rectifiers is to use a phase shift transformer for half the inverter load.

#### **11.4.2 Filters**

- PWM inverters should include DC link filtering incorporating reactance and inductance.
- This minimises the ripple current in the DC circuit and, therefore, does not affect the conduction point of the input diodes.
- Near unity power factor and a lower level of harmonic distortion reflected on to the supply results.
- AC line inductors can be used with inverters.
- These soften the waveform and improve the harmonics.
- They have a worthwhile effect on inverters without DC link filtering, and improve the power factor.
- They normally provide little improvement on inverters with DC link filtering, although they may be required where there are very long cable runs or high transients in the supply.
- Harmonics can also be filtered, although care should be taken with the design of the overall system for effective filtration.
- A harmonic filter basically comprises a capacitor connected in series with a reactor tuned to the frequency to be eliminated.
- In practice, the frequency used is slightly less to allow for the natural resistance of the circuit. This allows an acceptably small level of the harmonic current in the network.

- Single filters can increase the magnitude of lower frequency harmonics, where this occurs a multi arm filter is required.
- Careful analysis of the network is required for effective filtration.
- Multiple filters of the same frequency must not be used on the same network, as slight differences can cause one filter to take a larger share of the harmonic current.
- The differences can also cause a harmonic resonant condition which will amplify the very harmonic that was being treated.

#### **11.4.3 Power Factor Correction**

- Power factor correction capacitors present a low impedance at harmonic frequencies.
- They can therefore absorb harmonics and cause an increased voltage to be applied across the dielectric of the capacitor.
- This can cause overheating and premature failure of the capacitors.
- Power factor correction capacitors may resonate with the supply system inductance at the same frequency as one of the harmonics generated.
- This can magnify the value of the harmonic current flowing through the capacitor.
- This creates increased voltage distortion and again can lead to capacitor failure due to high voltage across the capacitor dielectric and excessive current in the capacitor ancillary components.
- The location of capacitors and changing the number of switching stages can affect the susceptibility to harmonics.
- Alternatively, a reactor may be installed in series with each capacitor although this may not be cost effective.

### **11.5 Reliability**

- There is always a balance between ideal operation, reliability and ease of repair.

#### **11.5.1 Mechanical Flow Control Devices**

- Mechanical flow control devices are likely to be reliable, but linkages are likely to cause imperfect operation due to hysteresis or when incorrectly adjusted.
- Simple mechanical items can often be repaired by labour with a low skill level which can be beneficial in getting the plant working again.
- Normally there is no method to bypass the items when they fail, although they usually continue to work in a fixed or reduced mode of operation.

#### **11.5.2 Variable Pitch Fans**

- Many variable pitch fans use pneumatic drives, which are normally very reliable, although the compressed air supply can cause problems.
- Where an instrument standard clean dry air supply is available there is no problem.
- Where a miniature compressor without effective drying or filtering is used for local compressed air, problems can occur due to dirt and moisture in the air supply.
- There is no method of bypassing the fan in the event of compressed air supply failure and the fan will normally fail to minimum flow.
- Hub linkages can be affected by dewpoint air and moisture carryover from humidifiers.
- Repairs can be expensive, long downtime can be experienced.

### **11.5.3 Inverter Drives**

- Frequency inverter drives have been available for a number of years.
- Some of the early drives were not very reliable and caused interference.
- This has caused some installers to be reluctant to use frequency inverters.
- Modern electronics are normally very reliable, and there is little need to be concerned about the reliability of frequency inverter drives, provided they are from a reputable source and are selected and installed correctly.
- One advantage with the frequency inverter is that where users are concerned about failure the drive can be bypassed and the motor run at full speed via a bypass starter.
- This does increase the cost of the installation and is not normally necessary where duty/stand-by or shared duty devices are used.
- Enclosure cooling is essential.
- In multiple assemblies, failure of cooling could result in all inverters tripping on high temperature.
- It is preferable to install inverters in individual panels or cubicles each with their own cooling.

### **11.5.4 Eddy Current Couplings**

- The eddy current coupling has a long history of reliable operation.
- There is no method of bypassing the coupling in the event of failure.
- The controller can be bypassed on more recent units by applying 240V to the coupling for full speed operation.

### **11.5.5 Switched Reluctance Drives**

- The switched reluctance drive is the most recent VSD.
- It utilises a controller with similar electronics to a frequency inverter plus a unique design of motor.
- The SRD has had a sufficient life to get over early teething problems and there is no reason why it should not be as reliable as an inverter drive system.
- There is no method of bypassing the controller/motor if required in the event of failure.
- Enclosure cooling is essential.
- In multiple assemblies, failure of cooling could result in all controllers tripping on high temperature.
- It is preferable to install controllers in individual panels or cubicles, each with their own cooling.

## **11.6 Frequency Inverters**

### **11.6.1 Sizing**

- Frequency inverters should be sized in accordance with the frame size of the motor used.
- Undersized inverters should not be used.
- Motors should be sized using conventional techniques with modern high speed switching PWM or voltage vector inverters.
- Other inverters may require that the motor has an additional capacity of up to 10%.
- Motors should have the rating marked as per the normal frame size.
- Considerable confusion can occur if the motor plate rating is reduced because of the derating effect of an inverter.

### **11.6.2 Motor Cooling**

- At low speeds the motor will have reduced cooling.
- This should not normally cause problems but where harmonics are present there may be an additional heating effect.
- Modern frequency inverter drives should not cause overheating.
- Where prolonged running at low speeds is likely, adequate motor ventilation should be ensured.

### **11.6.3 Starting/Isolation**

- Frequency inverters normally limit the starting current to 110% of full load current of the motor.
- Starting current is user adjustable on some units.
- Sequencing of items to prevent surge on start up is not necessary due to the limited in-rush current.
- Frequency inverters supplied for building services application provide variable torque characteristics suitable for most centrifugal pump applications.
- For constant torque applications inverters with suitable torque characteristics must be used.
- The rate of acceleration of devices also affects the torque characteristics, this is not normally a requirement for pump or fan applications.
- Oversized motors for rapid acceleration devices are also sometimes recommended; again this should not affect any building services application.
- Frequency inverters do not need separate starters although contactors may be required for emergency stop, etc.
- Most early frequency inverters could be damaged by use of contactors or isolators located on the output side of the VSD.
- Most modern frequency inverters have electronics that will tolerate contactors or isolators on the output side and therefore normal motor isolation methods can be used.
- Early break, late make, auxiliary contacts are recommended for control circuit interlock with the inverter to provide a controlled restart.
- Where an inverter bypass facility is required a standard motor starter, changeover switch, etc will be needed in addition for each motor.
- Most frequency inverters will normally tolerate a break in the power supply for up to 0.5 seconds without tripping.

### **11.6.4 Acoustic Noise**

- Frequency inverters typically produce between 35 and 55 dB(A) from a number of sources including cooling fans.
- Acoustic noise can vary in proportion to motor speed for some of the elements.
- The motor can have an increased noise by up to 10 dB(A) compared with normal 50 Hz operation.
- Noise levels can also vary dependent upon the mounting arrangements and the switching frequency.
- Inverters with variable switching frequencies can be tuned to reduce the levels of acoustic noise.

### **11.7 Switched Reluctance Drives**

- The SRD motor is unique but is compatible in size and fixing with an equivalent rating squirrel caged induction motor; no motor derating is required.
- A compatible controller must be used which is similar in size to a comparable frequency inverter.
- Due to the recent reduction in size of many inverters individual comparisons may be desirable.

### **11.7.1 Motor Cooling**

- The motor is designed for variable speed operation and no special requirements should be necessary for cooling.
- Thermistors are normally incorporated into the motors for overheat protection.
- Ambient temperature limits for the motor are normally -10°C to 40°C.

### **11.7.2 Starting/Isolation**

- The starting current is normally only 25% of full load current of the motor.
- This provides up to 150% of the rated torque on start up with a 1500 rpm motor, although this is lower with a 3000 rpm motor.
- Sequencing of items to prevent surge on start up is not necessary due to the limited in-rush current.
- SRDs do not need separate starters and normal motor isolation methods can be used.
- Early break, late make, auxiliary contacts are recommended for control circuit interlock with the SRD controller so that the motor will have a controlled restart.
- The SRD controller normally trips in the event of the power supply going out of limits.
- Transient interruptions of one phase for 3 cycles, or all phases for one cycle, are normally tolerated.
- An auto restart option is available if required.

## **11.8 Eddy Current Coupling**

### **11.8.1 Sizing**

- ECCs and motors are normally sold as an assembly.
- The motor is a standard squirrel caged induction motor and the ECC can be purchased separately.
- ECCs should be selected according to the output rating and maximum speed of the motor.
- Where belt drives are used, pulleys can be changed to allow for the reduced maximum speed from the ECC if required.
- A compatible controller should be used for the ECC.
- There are normally only a couple of models of controller for the full range of ECC sizes.

### **11.8.2 Starting/Isolation**

- This is all as per a normal squirrel caged induction motor.
- The controller normally trips in the event of power failure although auto restart options are available.
- The controller can be bypassed in case of failure with most recent ECCs by providing a 240 V AC supply direct to the coupling for full speed operation.

## **11.9 Multiple Speed Motors**

- Multiple speed motors require little in the way of special installation apart from the starter arrangement.
- Smaller motors, particularly close coupled pumps, have the speed selection in-built into the motor.
- More recent units allow automatic control from a remote location.
- An overload on a normal starter will not provide adequate protection at anything other than maximum speed.
- It is essential that the motor has an in-built thermal cut-out sensing the motor winding temperature.

- The thermal cut-out should preferably give remote indication for alarm and pump changeover.
- On larger motors a separate starter is required for each speed (normally only two speeds).
- An additional contactor is required for high speed operation for motors with a Dahlander form of connection.
- Dual speed motors with need for star-delta starting may need seven or more contactors - clearly VSDs are worth considering and are probably more cost effective and reliable.
- The exact starter/contacter connection requirements for the particular motor being used must be checked prior to specifying the starter/contacter arrangement.
- Control should comply with that detailed in the appropriate sections of the latest IEE regulations on MSMs.

#### **11.10 Inlet Guide Vanes**

- Fans with IGVs should be supplied as a fully tested assembly with full works test certification for maximum and minimum volume/pressure duties.
- Linkages must be able to operate over the full movement and be adjustable to provide the correct range of operation.
- Actuators must be fixed to rigid brackets to prevent unwanted movement.
- Linear actuators which require angular movement should be suitably mounted on a rigid bracket with a pivoting mounting.

#### **11.11 Dampers**

- Dampers are available in parallel and opposed blade formats.
- Opposed blade dampers should be used for throttling applications.
- To provide good modulating control, dampers should be sized to give the correct authority.
- This is rarely done as it restricts maximum flow and little data is normally available to enable the sizing to be calculated.
- If located adjacent to air intake and weather louvres, damper must be duct size to avoid excessive velocities and to maintain effectiveness of louvres, and to minimise noise break-out.
- The opposed blade damper gives an installed flow to opening characteristic with an authority of around 0.1 whilst the equivalent figure for a parallel blade damper is around 0.25.
- Therefore, an opposed blade damper of duct size is likely to give good control if its pressure loss fully open is about 10% of the loss in the rest of the system.
- This will give significant energy savings over a parallel blade damper when each are correctly sized for control.
- In the normal situation where the damper is installed at duct size, much better control will result from the use of opposed blade damper.
- Control will not be as good as if the damper were correctly sized but where closed loop control is used it should be adequate.
- Linkages must be able to operate over the full movement and be adjustable to provide the correct range of operation.
- Actuators must be fixed to rigid brackets to prevent unwanted movement.
- Linear actuators which require angular movement should be suitably mounted on a rigid bracket with a pivoting mounting.

### 11.12 Variable Pitch Fans

- The installation of a variable pitch fan differs little from that of a fixed pitch axial fan.
- Minimum distances from the fan inlet and outlet should be maintained and access must be made available to enable maintenance and repair of components.
- Variable pitch fans normally have pneumatically actuated variable pitch mechanisms, electro-pneumatic and electric-actuation is also available.
- For electronic, DDC or building management systems, pneumatic actuation with a clean dry air supply for good control and reliable long term operation is recommended.
- This should not add that much to the overall cost, especially where a number of fans are being installed as only one compressor set will normally be required.
- Minimum start up time and reduced current can be achieved by interlocking the control system to return the fan to minimum pitch on shutdown.
- Anti condensation heaters may be required in the actuator housing for some applications.
- Stall detection is essential for variable pitch fans.
- Operation should be to 'back-off' from under stall conditions until the fan is out of the stall condition.
- Stall detection should be linked to alarm signals.
- The fan motor fuses, starting, isolation and cabling are all as per a normal squirrel caged induction motor.
- Care should be taken to ensure that the correct control method is chosen for the application and not the cheapest solution available from the supplier.

#### Pneumatic actuation

- The variable pitch fan requires a 25 or 20 psi supply to the positioner and a 3 to 15 psi signal for pitch control.
- Some early fans with external actuators required higher pressures for the positioner supply, typically 75 psi.
- The compressed air supply should be clean and dry.
- A separate duplex air compressor set with a receiver, suitable filtration and a refrigerated air drier is recommended.
- Positioners should always be used to prevent hysteresis in the pitch control due to friction in the linkage.
- Position feedback should be from an in-built fan feedback potentiometer, not the actuator.
- In the event that feedback is not used, closed loop control of air flow on extract fans must be used to ensure good control.
- Some suppliers provide a number of control solutions to overcome these problems and provide synchronised supply and extract fans if required.
- An electro-pneumatic transducer should be used to convert an analogue controller output to a 3 to 15 psi control signal.

#### Electro-pneumatic actuation

- Some fans claimed to have electric actuation actually have electro-pneumatic actuation.
- The miniature compressors do not have any provision for drying the air and can cause control problems.

- Filters or dryers can be used with these compressors and are claimed to solve the moisture problem.
- Where electrical, DDC or building management systems are used, the normal method of control is a three point control signal which allows the blade angle to increase, stay the same or decrease.
- This is normally linked with the mini compressor operation and results in rapid change in pitch and unstable control.
- A slugging device must be used to give a pulsed signal to the electro-pneumatic relays.
- Some electronic controllers have pulsed signal outputs with slugging.
- The quality of control with this method of operation is likely to be much poorer than with pneumatic control, even disregarding the potential problems created by the mini compressor.
- This is due to the slugging of control operation and the inaccuracy and hysteresis due to the lack of blade position feedback in the control loop.

#### Electric actuation

- Generally limited availability due to torque and mechanism.
- Availability increasing.
- Actuator input signal should be compatible with control output signal.

### 11.13 Control System Interfacing/Communications

- Serial link communication facilities are often provided with frequency inverters and SRD controllers.
- ECCs and mechanical devices do not normally have any serial link communication facilities.
- Serial link communication facilities have not often been used for control via DDC/BMS due to lack of suitable protocols.
- Some BMS suppliers are now working with drive suppliers to ensure compatibility.
- An analogue signal (often 0 to 10 V) can normally be used for speed control with VSDs.
- A volt free signal is used for start/stop and volt free contacts for alarms are often provided. VSDs with additional in-built control algorithms are also available and sometimes can reduce the overall cost of installations.

### 11.14 Location/Housing

- Inverters and SRD controllers should preferably be mounted in a cubicle type control panel to minimise emission of, and susceptibility to, RFI and to provide a clean dry environment.
- The inverter or SRD should be mounted flush with the panel facia, or a window provided to allow access to settings with the equipment in operation.
- Some inverters are now available with facia panels connected to the inverter via a ribbon cable.
- Facia panels can be panel door mounted to provide access to control functions without opening panel cubicles.
- Locks or security codes may be desirable to prevent unauthorised interference.
- Some inverters and SRDs have in-built fans for cooling although when mounted in control panels additional fans may be required to ensure adequate ventilation.

- It should be noted that a temperature 15°C above the maximum rated temperature can cause an inverter to be derated by 50%. Most inverters and SRDs have an in-built over-temperature alarm. A separate over-temperature alarm should be considered where panel mounted units do not have an in-built alarm.
- Where inverters and SRD controllers cannot be mounted within a control panel, a clean dry location should be provided where the settings can be reached without difficulty.
- The ECC controller is much smaller than the equivalent inverter or SRD controller and purely provides the control function without any power rectification, etc.
- Panel facia and rack mounting ECC controllers are available.
- Normally, temperatures should be between 0 and 40°C and relative humidity below 95%, condensation free. Anti-condensation heaters may be required within control panels for some inverters, particularly if the units are to be stored on site for a period of time prior to operation.

### **11.15 Cabling**

- All cabling methods and types should be installed in accordance with supplier's instructions to conform with methods used for testing and certification of the product.
- Cabling must also be installed in accordance with the appropriate sections of the latest IEE regulations.

#### **11.15.1 Power Cables**

- The motor cabling requirements of SRDs and inverters are generally similar, except that an SRD requires a six core SWA cable and an inverter a three core SWA cable.
- Cabling between inverters, or SRD controllers, and the motor should preferably be kept as short as possible.
- Within reason, preference should be given to housing the inverter, or SRD controller, in a suitable control panel.
- To comply with the forthcoming certification requirements SWA cable with improved RFI screening may be required together with specific methods for termination of the armour.
- Some suppliers recommend that a four core SWA cable is used instead of a three core SWA cable between inverters and motors.
- The fourth core should be used for the earth and the steel wire armour used as an RFI screen.
- The earth core should be connected to the inverter earth terminal and not the common busbar at the inverter end.
- The steel wire armour in this instance should be earthed at the inverter end only to avoid any current loops in the armour.
- RFI on inverter and SRD controller supply cables normally increases with longer motor cables.
- An RFI filter may be required on the supply cable dependent on emissions.
- Panel mounted inverters and SRDs should have the power supply cable segregated from other cables to avoid RFI pick-up by other cables.
- A locally mounted inverter or SRD may also require the power cable to be screened in a similar manner to the motor cable.
- Requirements for CE certified devices will be detailed by suppliers to ensure conformity.
- ECC motor power cabling has no special requirements and should be as per a normal squirrel caged induction motor.

### **11.15.2 Control Signal Cables**

- Control signal cables should normally be screened.
- Screening should normally be earthed at one point only, at the controller or panel terminal rail.
- The screening should preferably continue within the control panel to the controller or VSD.
- Cables within an enclosure should be segregated so that mains and signal cables are not grouped together.
- Signal cables should not run in parallel to power cables external to the panel.
- SRDs require an additional six core cable for control signals between the controller and motor.
- A two core cable is normally required for isolator interlock to permit controlled restart of motors.

### **11.16 Fuses**

- Frequency inverters and SRDs normally require the use of fast acting semi-conductor fuses to protect the electronics, rather than the high rupture capacity type normally used for motors with conventional starters.
- These fuses are normally installed at the inverter with high rupture capacity fuses installed in the distribution board.

### **11.17 Power Factor Correction**

- Power factor correction is required where power factor is poor. This avoids increased electricity charges.
- Where power factor is poor, reactive power increases and can cause overloading of motor power cables.
- Local power factor correction may be used to avoid overloading of motor power cables and can be used in association with power factor correction at the point of supply.
- Where poor power factor is caused by lightly loaded constant speed motors cable overloading is unlikely.
- Where power factor varies due to variable motor loads, such as variable pitch fans, automatic power factor correction is required.
- Where harmonics are present please also see section 11.4.3.

### **11.18 Critical Speeds**

- Where any form of variable speed control is used for fans, critical speeds which cause resonance must be avoided.
- If critical speeds fall within the range required for speed control, the control system must be arranged to accelerate through the speed range as quickly as possible and not to allow the critical speed to be held.
- This is not normally a problem on centrifugal fans but occurs more frequently on propeller fans.
- Good dynamic balancing of the fan helps to avoid resonances.
- Anti-vibration mounts are normally selected with a natural frequency of one third of the fan/pump speed.
- This should be reduced to below the minimum speed where variable speed drives are used.
- This is normally of more concern with a fan than a pump due to the relative mass of components and methods of installation.

### 11.19 Multiple Motors

- Where multiple motors are run from one inverter, suitable protection must be provided for each motor for over-current operation, and loss of phases where appropriate.

### 11.20 Commissioning

- Variable speed motor controllers (inverters, eddy current couplings, switched reluctance etc) require specialist commissioning.
- The methods used for set-up varies between devices, there being a range of meanings associated with setting parameters.
- Operating temperature checks should be made to confirm operation is within manufacturer's ratings.
- Due account should be taken of heat gain from other equipment that may not be fully loaded at the time of commissioning, eg boilers.

### 11.21 Safety

- DC link capacitors remain charged for some time after mains isolation and the voltage is potentially lethal.

The following points need to be specifically addressed.

- Ensure that bleed resistors are included by the inverter supplier to discharge the capacitor.
- Provide warning labels advising operatives to wait for a time (as recommended by supplier) before removing covers.
- Some inverters (mainly older machines) have internal adjusting potentiometers needing adjustment with the inverter live.
- Ensure that adjustment can be carried out safely without risk of shock.
- Many inverters particularly imported devices, are in very basic IP2x enclosures with no means of isolation.
- Due to the lethal shock hazards, it is recommended that inverters are protected to IP2x, then this assembly is enclosed in either a local panel or an individual cubicle of a motor control panel.
- Either case should protect to IP4x or better and use door-interlocked isolation with both internal and external warning labels.
- Keypad display must be accessible without isolating the drive, otherwise alarms/diagnostics stored in memory will be lost when power is switched off.
- Most drives have an option for remote location of keypad/display on the front panel.
- When multiple inverters are installed in a single panel section, individual isolation needs to be provided for safe working without isolating all inverters.

## 12. MAINTENANCE

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- Guidance in this section can only be of a general nature and covers the additional maintenance likely to be required by the variable flow components of the system.
- Please refer to the HVCA Standard Specification for Maintenance of Mechanical Services for overall maintenance requirements of services.
- Manufacturer and specialist supplier maintenance procedures should be followed for specialist equipment.

### 12.1 Safety Checks

- Safety checks must be carried out in accordance with manufacturers recommendations and the latest IEE regulations.

### 12.2 Monitoring

- The operation and performance of systems should preferably be continuously monitored to ensure energy efficient operation.
- The use of building management systems enable monitoring in a cost effective manner.
- Now that most control systems for building services are microprocessor based, the additional cost of a supervisory facility is relatively low.
- Additional points may be required for monitoring, such as inputs from meters.
- Care should be taken to ensure that systems are correctly specified for the functions required, as inadequate specifications can lead to poor installation and performance, and over specified systems can be very costly.

### 12.3 Belt Drives and Bearings

- Belt drives and bearings should have a longer life and require less maintenance where variable speed drives are used due to the 'soft start' and reduced speed operation.

### 12.4 Filters

- All filters (including panel, inverter, etc. cooling fan filters) where fitted must be regularly inspected, and cleaned or replaced as necessary.

### 12.5 VSDs

- VSDs do not normally require any form of scheduled maintenance.
- Maintaining a clean dust free environment is strongly recommended for correct operation.
- Checking the settings of the units should be done periodically to ensure that there has been no interference with, or corruption of, the settings.
- Where no problems are normally found, checks will only be required on a regular basis in accordance with plant maintenance procedures.
- SRD motors should require only regular checking and cleaning as per squirrel cage induction motors.
- ECC drive couplings should have an audible and visual inspection every 12 months.
- Faults with the units will require repair by the manufacturer or specialist supplier.

### 12.6 Multiple Speed Motors

- Multiple speed motors require little in the way of special maintenance, apart from regular checks to ensure that the motors are operating at the speeds as required by the control system.
- Motors should have regular checks, cleaning and lubrication, as per any other squirrel caged induction motor.
- Switchgear should be regularly checked, tested and vacuumed, as per normal switchgear requirements.

## **12.7 Inlet Guide Vanes, Disc Throttles and Dampers**

- Checks and required maintenance should be carried out or in accordance with plant maintenance procedures, preferably at regular intervals of no more than six months.
- Guide vanes, disc throttles and dampers should be cleaned and moving parts lubricated as required.
- Actuator and linkage operation should be checked for calibration at minimum, mid point and full stroke.
- Operation should be checked to be smooth without undue hysteresis.
- Linkages should be lubricated, as required, and adjusted as necessary to ensure correct operation.
- Brackets and fittings should be checked for movement and secure fastening.

## **12.8 Variable Pitch Fans**

- Checks and required maintenance should be carried out at manufacturers recommended service intervals of no more than six months.
- Air compressors and dryers may require checks and maintenance at three monthly intervals, or more frequently depending on the conditions and the particular equipment involved.
- Inspection at weekly intervals may be necessary.
- Variable pitch fans should be cleaned and moving parts lubricated as required.
- Actuator and linkage operation should be checked for calibration at minimum, mid point and full stroke.
- Operation should be checked to be smooth without undue hysteresis.
- Linkages should be lubricated as required and adjusted as necessary to ensure correct operation.
- Brackets and fittings should be checked for movement and secure fastenings.
- Pneumatic compressors should be checked for starting and stopping at the correct pressures.
- Air receivers and compressed air moisture removal filters should be drained of any moisture.
- Compressor oil and all filters (including air inlet) should be changed on an hours run or time elapsed basis (note: the correct oil for the compressor must be used).
- Duplex compressors should be checked for changeover as required.
- Pressure regulators should be checked for maintenance of correct supply pressures.
- Compressed air filters should be changed on a time elapsed basis.
- Refrigerated air driers should be checked that they cool the air to the required temperature and any moisture drains operate correctly.
- Desiccant air driers or other types of air drier should be checked in accordance with the manufacturer's instructions.
- Controllers and electro pneumatic transducers should be checked for correct operation.
- Miniature air compressors and their ancillary devices should be maintained according to the manufacturer's instructions.
- Miniature air compressors normally require rebuilding with new piston rings every 10 000 hours of operation.
- Moisture build up and consequential poor control can be a problem with miniature air compressors as the compressed air is not normally dried.

### 13. GOOD PRACTICE RECOMMENDATIONS

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- Significant savings can be achieved by both system regulation and variable flow control.
- VSDs should be considered for energy efficient regulation of fans and pumps rather than energy wasteful mechanical system regulation.
- Regulation savings are typically 20% for 10% regulation and 40% for 20% regulation.
- Variable flow control should be considered for all applications where the load changes due to local or seasonal demand.
- A typical variable flow system can show annual energy savings of over 25%.
- Savings greater than 50% are not uncommon.
- Paybacks of less than two years are common.
- Technical advances have made many forms of variable flow control more reliable and efficient.
- Careful system design and engineering is necessary to ensure energy efficient and reliable operation.

## 14. FINDINGS OF A UMIST VAV RESEARCH PROJECT (FUNDED BY EPSRC)

I. Khoo, G. J. Levermore, K. M. Letherman Department of Building Engineering  
UMIST, Manchester M60 1QD UK. January 1996.

### 14.1 Network Analysis

#### 14.1.1 Duct Resistance Concept

- To analyse VAV networks, the simple equation below is useful for analysis:

$$\Delta P = R V_{\dot{v}}^2 \quad \dots(1)$$

where  $\Delta P$  Pressure loss across the ductwork or fitting (Pa).

$R$  Ductwork or fitting resistance.

$V_{\dot{v}}$  Volume flow rate through the duct ( $\text{m}^3/\text{s}$ ).

- The ductwork and fittings' resistances can be combined into a system resistance. This gives the operating point, as in Figure 25.

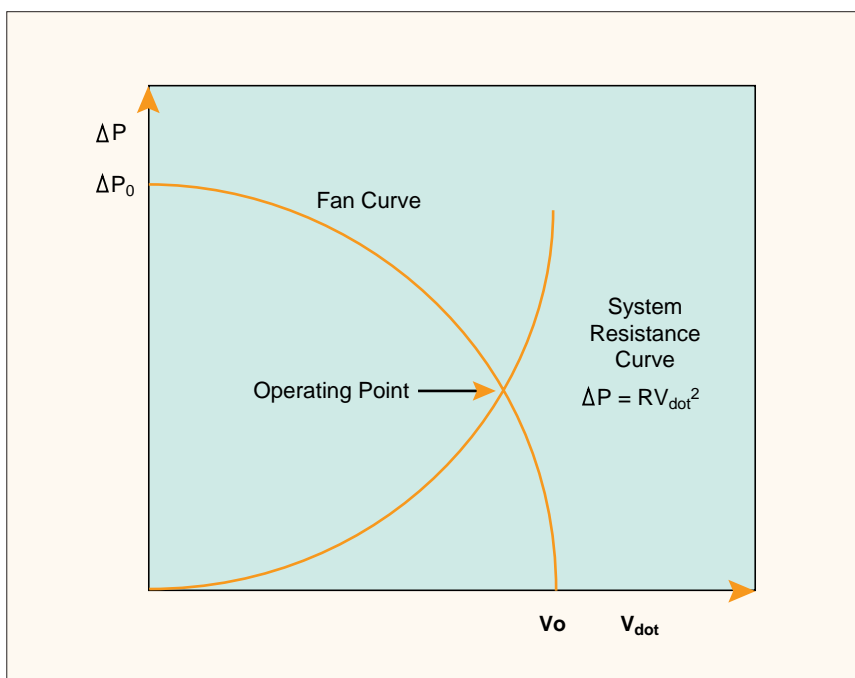


Figure 25 Fan and system curves

- The fan curve as shown in Figure 25 is defined by the following equation:

$$\Delta P_{\text{fan}} = n^2 \Delta P_0 - b V_{\dot{v}}^2 \quad \dots(2)$$

where  $\Delta P_{\text{fan}}$  Fan pressure (Pa).

$n$  Fan speed ratio (fan speed/maximum fan speed).

$\Delta P_0$  Fan pressure at zero volume flow (Pa).

$b$  Fan characteristic constant.

- In a VAV system many boxes are in parallel. For two equal resistances,  $R$ , in parallel the equivalent resistance is  $R/4$ . This means that VAV networks can change their resistance considerably.
- The square law of Equation 1 is an approximation, a more accurate formula for ductwork is:

$$\Delta P = 0.019 d^{-4.93} V_{\dot{v}}^{1.86} L \quad \dots(3)$$

where  $d$  Diameter of the duct (m).

$L$  Length of ductwork section (m).

### 14.1.2 Duct Size Implications

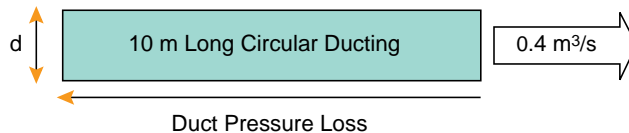
- Equation 2 has major implications for the power consumption in high velocity, low diameter ductwork as:

$$\text{Fan Power} = \Delta P_{\text{fan}} V_{\text{dot}} \quad \dots(4)$$

ie Fan Power  $\propto d^{-4.93}$

#### Example

Consider the power requirements to drive 0.4 m<sup>3</sup>/s along a 10 m length of duct.



0.40 m<sup>3</sup>/s along 10 m of 0.35 m duct has a pressure drop of about 6 Pa,

power = 2.4 W

0.40 m<sup>3</sup>/s along 10 m of 0.20 m duct has a pressure drop of about 96 Pa,

power = 38 W

Network analysis allows part load performance of VAV systems to be assessed.

### 14.2 Idealised VAV Systems

- VAV systems are complex but two idealised cases (a synchronous system and an asynchronous system) can help to understand them. Many practical systems will fall between these two cases.

#### 14.2.1 Synchronous System

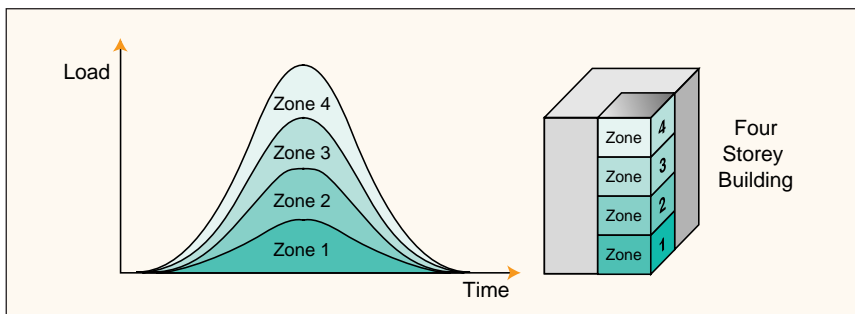


Figure 26 Synchronous load distribution with 4 zones

- Example; corner of a multi-storey building, a number of floors served, loads vary together; fan flow rate and power varies widely.

#### 14.2.2 Asynchronous System

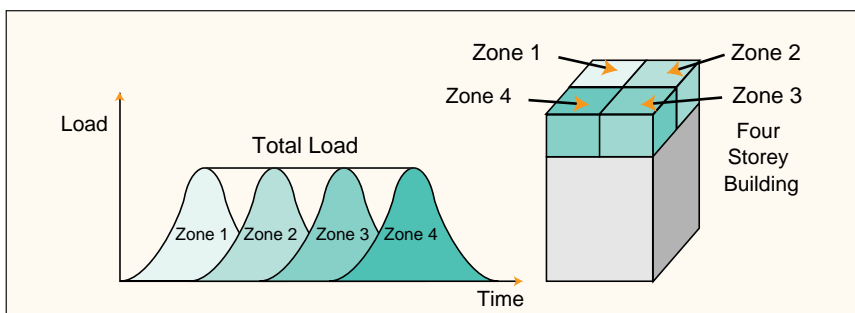
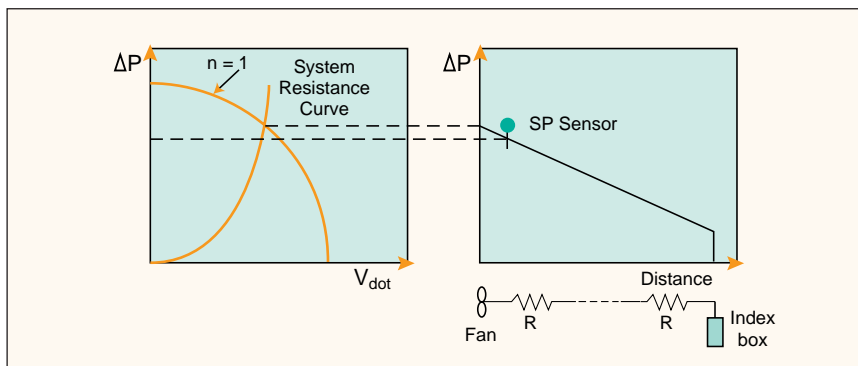


Figure 27 Asynchronous load distribution with 4 zones on one floor

- Example; one floor, many zones, equal loads, total load virtually constant, perfect diversity, fan speed and power varies little.
- Note saving made in design, capital and running cost; smaller fan and plant.

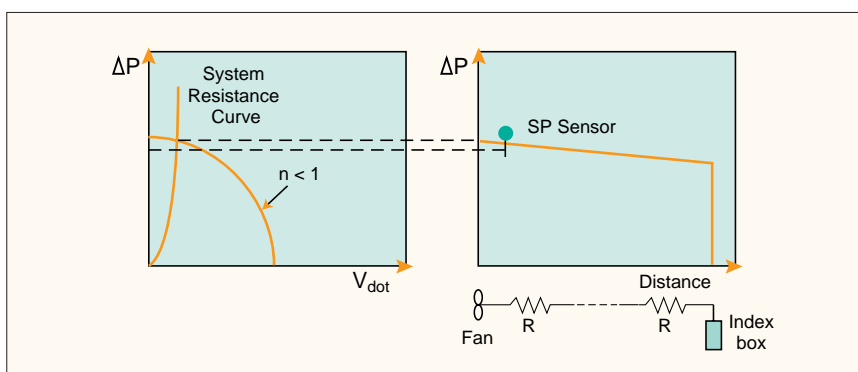
### 14.3 Potential Savings of a Synchronous VAV System

- At design conditions (figure 28).



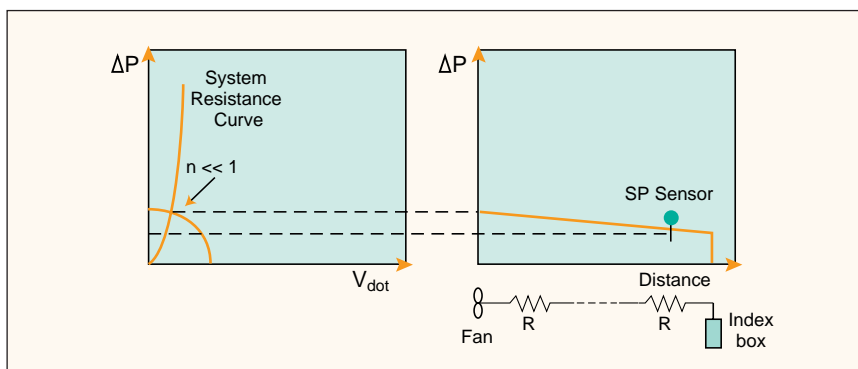
**Figure 28 Fan operation curve and duct pressure distribution curve (with static pressure sensor close to fan)**

- At almost zero flow, little fan speed reduction  $n < 1$  but close to 1 (figure 29).



**Figure 29 Fan operation curve and duct pressure distribution curve (with static pressure sensor close to fan)**

- With static pressure sensor further down, the static pressure can drop much lower, greater savings. Possible starvation upstream of sensor, starvation occurs when a box has insufficient pressure to maintain its required volume flow (figure 30).



**Figure 30 Fan operation curve and duct pressure distribution curve (with static pressure sensor close to index VAV terminal box)**

- Box polling and resetting static pressure can aid further pressure reduction.

NB: It has been assumed that the proportional plus integral (P&I) fan static pressure controller, which maintains the static pressure at the sensor, is constant.

#### 14.4 Fan Energy Savings with VAV Systems

- Traditionally people relate VAV savings to the fan laws; Fan power =  $\Delta P_{\text{fan}} V_{\text{dot}}$  or  $R V_{\text{dot}}^3$ . But for VAV systems R varies and the control system can constrain  $\Delta P$ .
- Often it is assumed that savings are proportional to (fan speed)<sup>3</sup> or  $n^3$ , (for the fan laws see Section 2.1).
- VAV fan speed savings do not follow this cube relationship.
- Fan savings = full load fan power - part-load fan power.
- Using network analysis and the fan equation, equations 2 and 5 can be obtained.

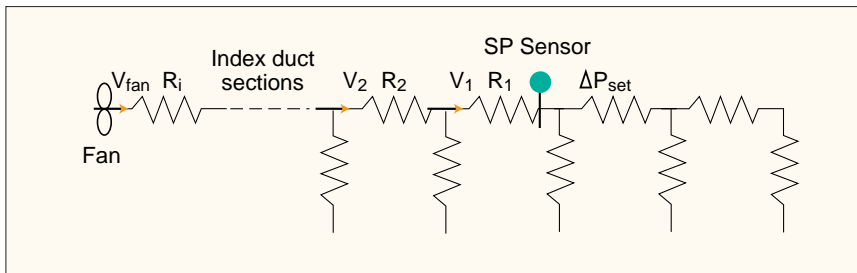


Figure 31 Duct resistance network

$$\text{Fan Savings} = \left[ \frac{2}{3} \Delta P_o + \frac{1}{2} \rho \frac{V_{\text{des}}^2}{A_{\text{fan}}^2} \right] V_{\text{des}} - \left[ \Delta P_{\text{set}} + \frac{1}{2} \rho \frac{V_{\text{sensor}}^2}{A_{\text{sensor}}^2} + (\sum R_i V_i^2) \right] V_{\text{fan}} \quad \dots(5)$$

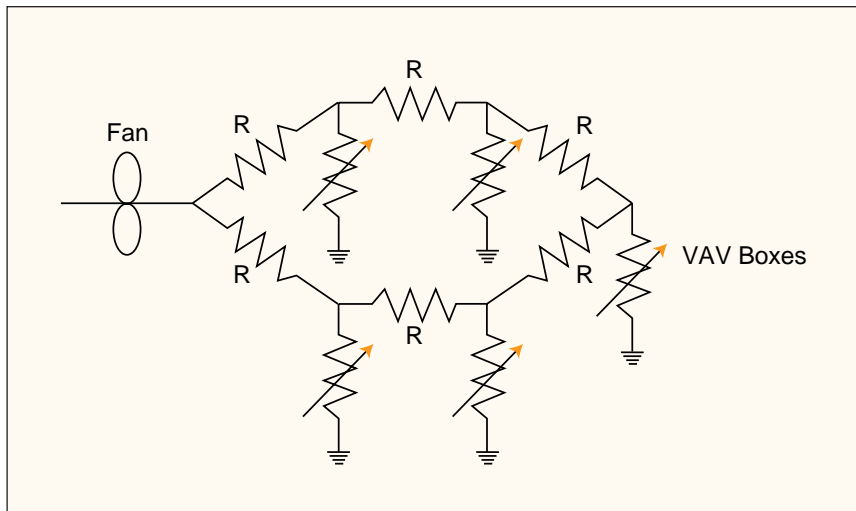
where	$\rho$	Density of air (kg/m <sup>3</sup> ).
	$V_{\text{des}}$	Design system volume flow rate (m <sup>3</sup> /s).
	$A_{\text{fan}}$	Area of fan outlet (m <sup>2</sup> ).
	$\Delta P_{\text{set}}$	Static pressure sensor set-point (Pa).
	$V_{\text{sensor}}$	Volume flow rate at static pressure sensor location (m <sup>3</sup> /s).
	$A_{\text{sensor}}$	Area of ductwork at static pressure sensor location (m <sup>2</sup> ).
	$R_i$	Resistance of index duct sections upstream from the static pressure sensor location.
	$V_i$	Volume flow rate of index duct sections upstream from the static pressure sensor location.
	$V_{\text{fan}}$	Volume flow rate at the fan outlet (m <sup>3</sup> /s).

NB Please refer to figure 31 for illustration.

- So if the static pressure sensor were to be placed closer to the supply fan, the power term related to  $\Delta P_{\text{set}}$  will dominate, thus equation 5 becomes more like a linear law.
- And as the static pressure sensor gets further from the fan,  $\Delta P_{\text{set}}$  will tend to a smaller value. Hence equation 5 becomes more like the cube law savings as in the fan laws.

#### 14.5 Duct Loops

- Traditional reducing of ductwork size along the index run (eg constant pressure loss design method) increases resistance and fan power requirement.
- Often, equal size ductwork saves capital cost as well as fan power requirements.
- Far more fan power savings are possible with the use of a duct loop (figure 32).



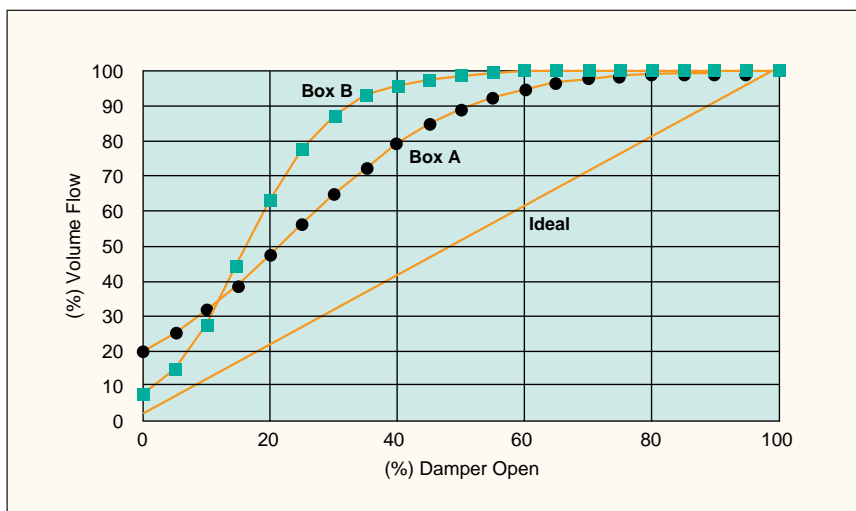
**Figure 32 Duct resistance layout of a duct loop VAV system**

- Savings for a synchronous system with a duct loop can generally be about 40% compared to a reducing size, single duct layout.
- Note filters and coils before the fan contribute to a considerable resistance to the system.

#### 14.6 Refrigeration vs Fan

- Although the chiller may be more powerful than the fan, there may be a tendency to reset the supply air temperature before reducing fan speed. In the UK, fan speed reduction may well save more initially; flow reduction saves fan power and chiller power.
- It is worth monitoring fan and compressor energy to verify the control strategy and to estimate savings; systems vary.
- Note the Department of the Environment's Energy Consumption Guide 19 shows that the annual refrigeration energy is typically much less than that for the fans, pumps and controls in offices.

#### 14.7 Pressure Independent Boxes



**Figure 33 Installed flow characteristics of two typical VAV terminal units**

- Both Box A and Box B are not ideal which is not unusual. But at low flow, control is difficult and the terminal box can become unstable.
- Pressure independent boxes are not always self balancing and stability depends on the quality of the box (Box A is better than Box B).

- The fan should be controlled slower than the boxes to stop it becoming unstable.
- For the two typical pressure independent VAV boxes, the following steady state models were derived from experiments.

$$\text{Log}_e (K' \times 10^{-6}) = -13.5 + 0.00437 \cdot \text{Da}^{1.77} \text{ (Box A)} \quad \dots(6)$$

$$\text{Log}_e K' = 0.332 + 3.68 \cdot 10^{-7} \cdot \text{Da}^{4.5} \text{ (Box B)} \quad \dots(7)$$

where  $K'$                       The total pressure loss factor of the terminal unit  
 $\text{Da}$                               The damper angle of the terminal units  
                                     Box A damper angle limits - 0 - 61.5 degrees  
                                     Box B damper angle limits - 0 - 45 degrees

- To obtain the total pressure loss across each of the boxes the velocity pressure at the inlet is multiplied with the  $K'$  values as shown.

$$\Delta P_{\text{Total}} = K' \cdot \frac{1}{2} \rho v^2 \quad \dots(8)$$

where  $\Delta P_{\text{Total}}$               Total pressure across the terminal unit (Pa).  
 $v$                                 Air velocity at the terminal unit inlet (m/s).

- These terminal unit models can be used for more detailed simulation.

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